Renewable Energy

2008

GEOTHERMAL ENERGY

António F. O. Falcão
Instituto Superior Técnico
Lisbon

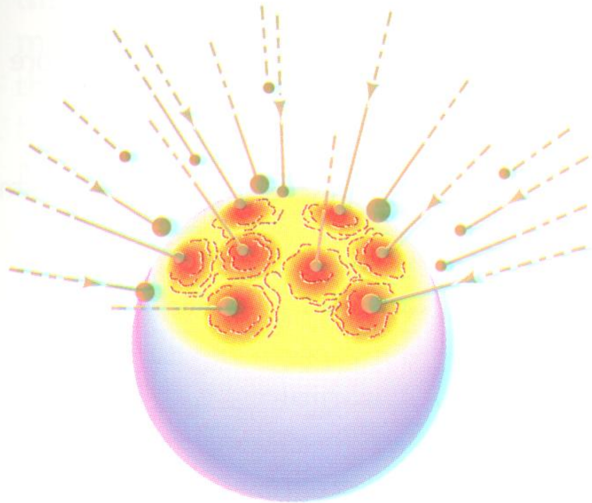
INSTITUTO SUPERIOR TÉCNICO

Geo means **Earth**

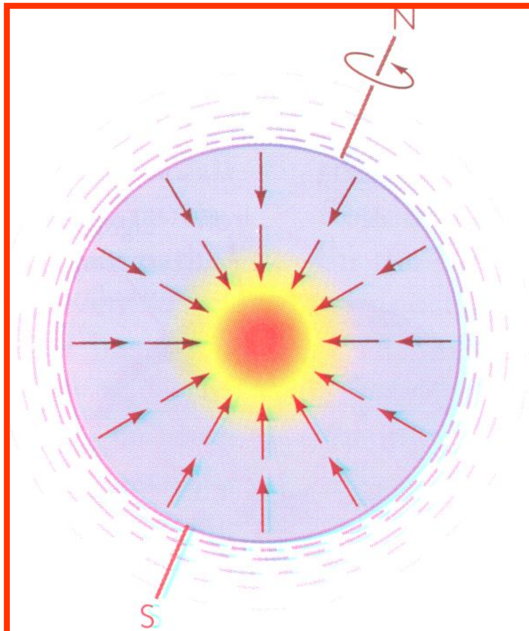
Thermal means **Heat**

Geothermal energy is the natural heat of the Earth.

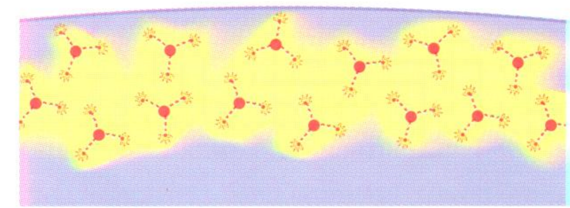
Mechanisms that caused the early Earth to heat up



(a) In accretion, colliding bodies bombarded Earth and their kinetic energy was converted to heat.

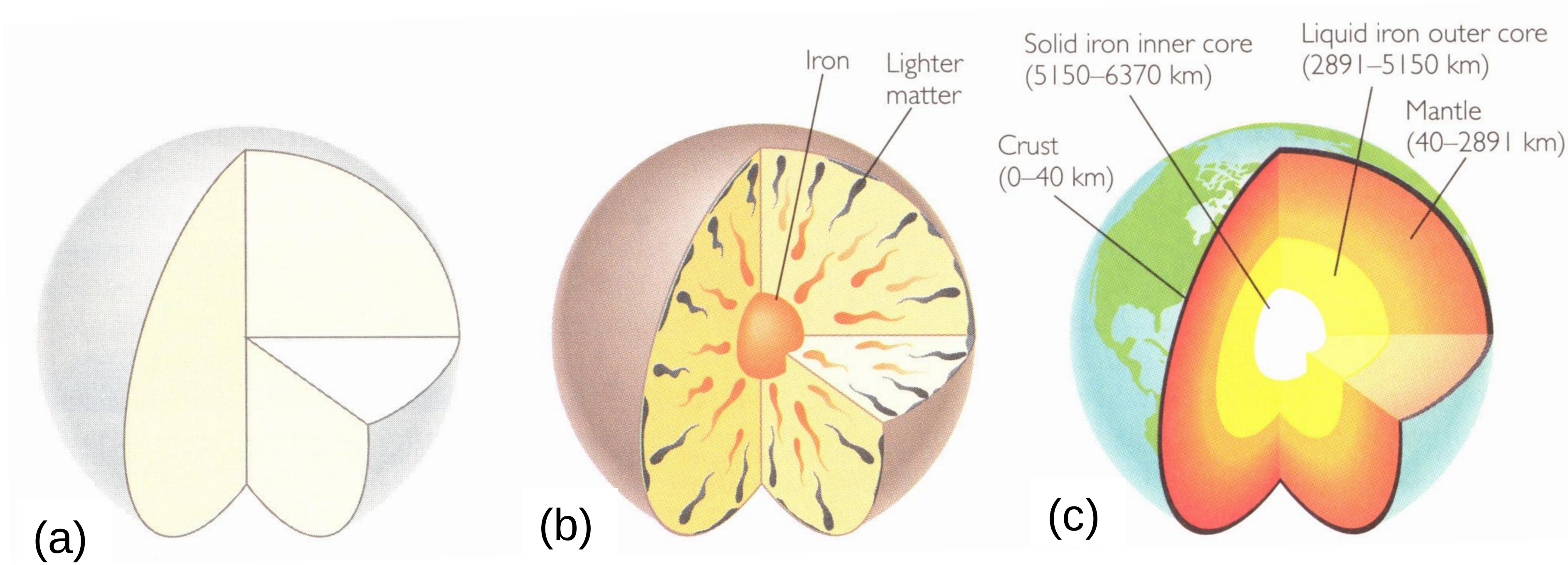


(b) Gravitational compression of Earth into a smaller volume caused the interior to heat up.



(c) Radioactivity of some elements (uranium and others).

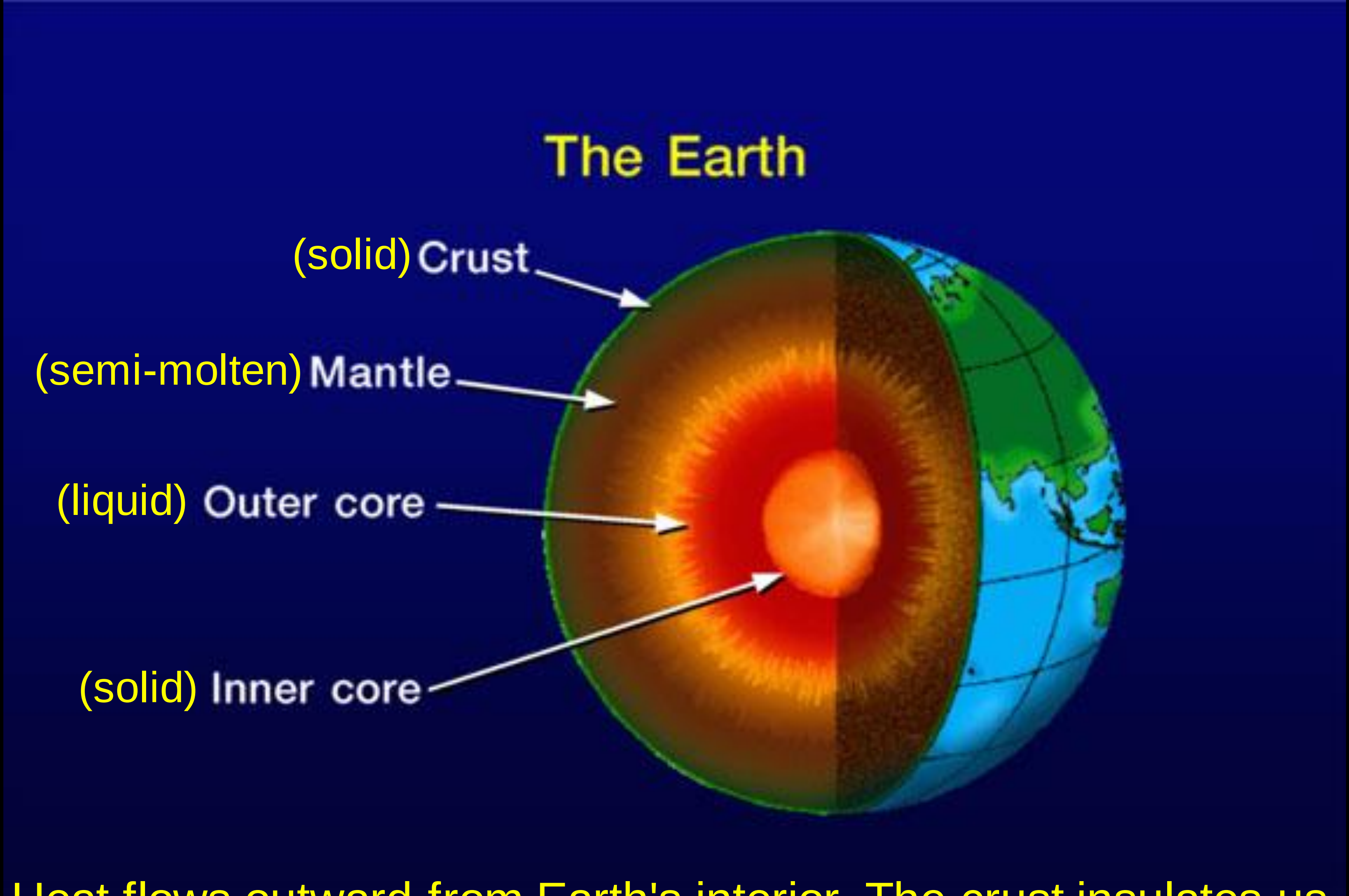
Process of differentiation of Earth



Early Earth was probably a homo-geneous mixture.

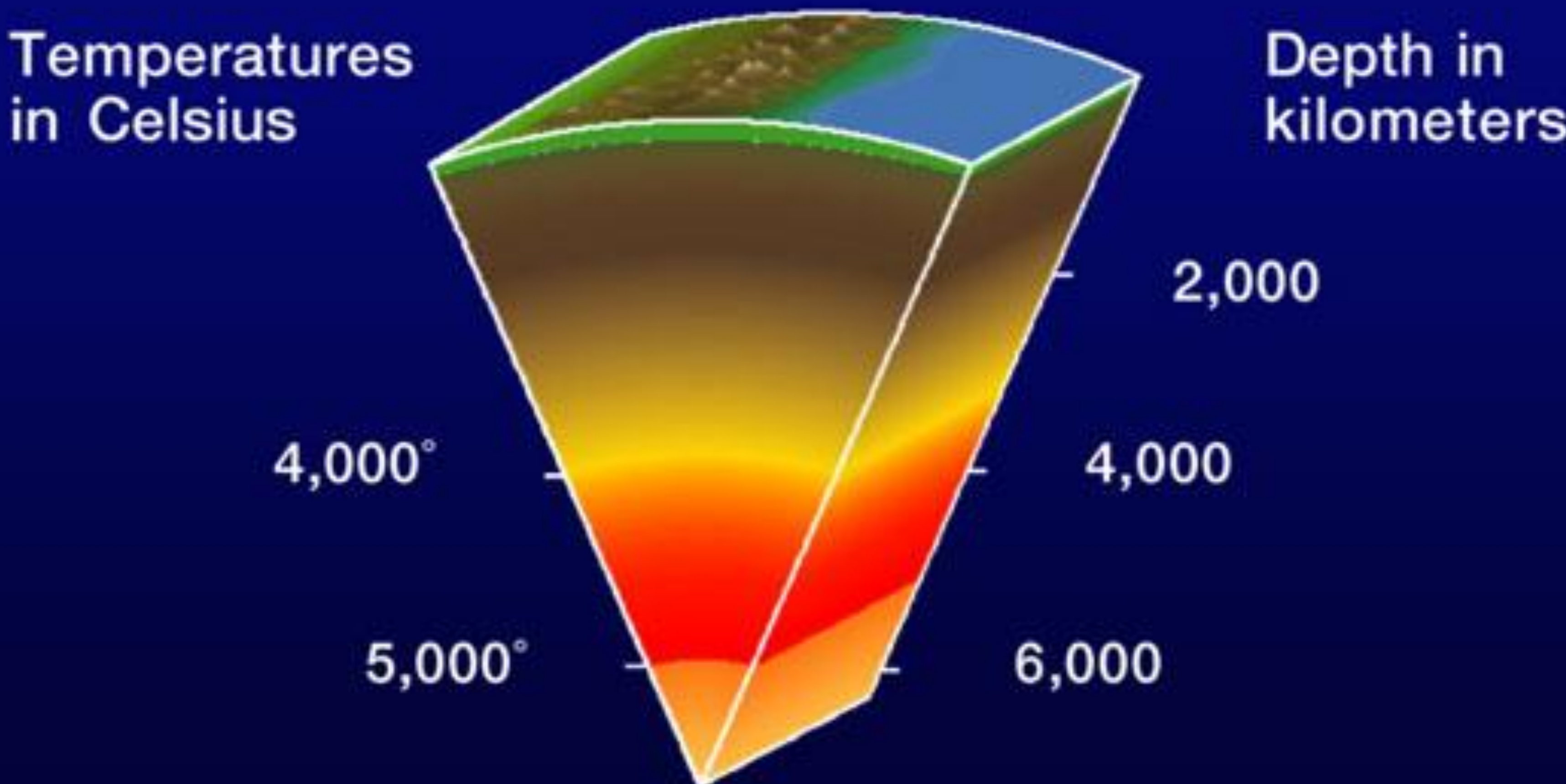
In the process of differentiation, iron sank to the centre and light material floated upward to form the crust.

Earth is a zoned planet, with a dense core, a crust of light rock and a residual mantle between them.

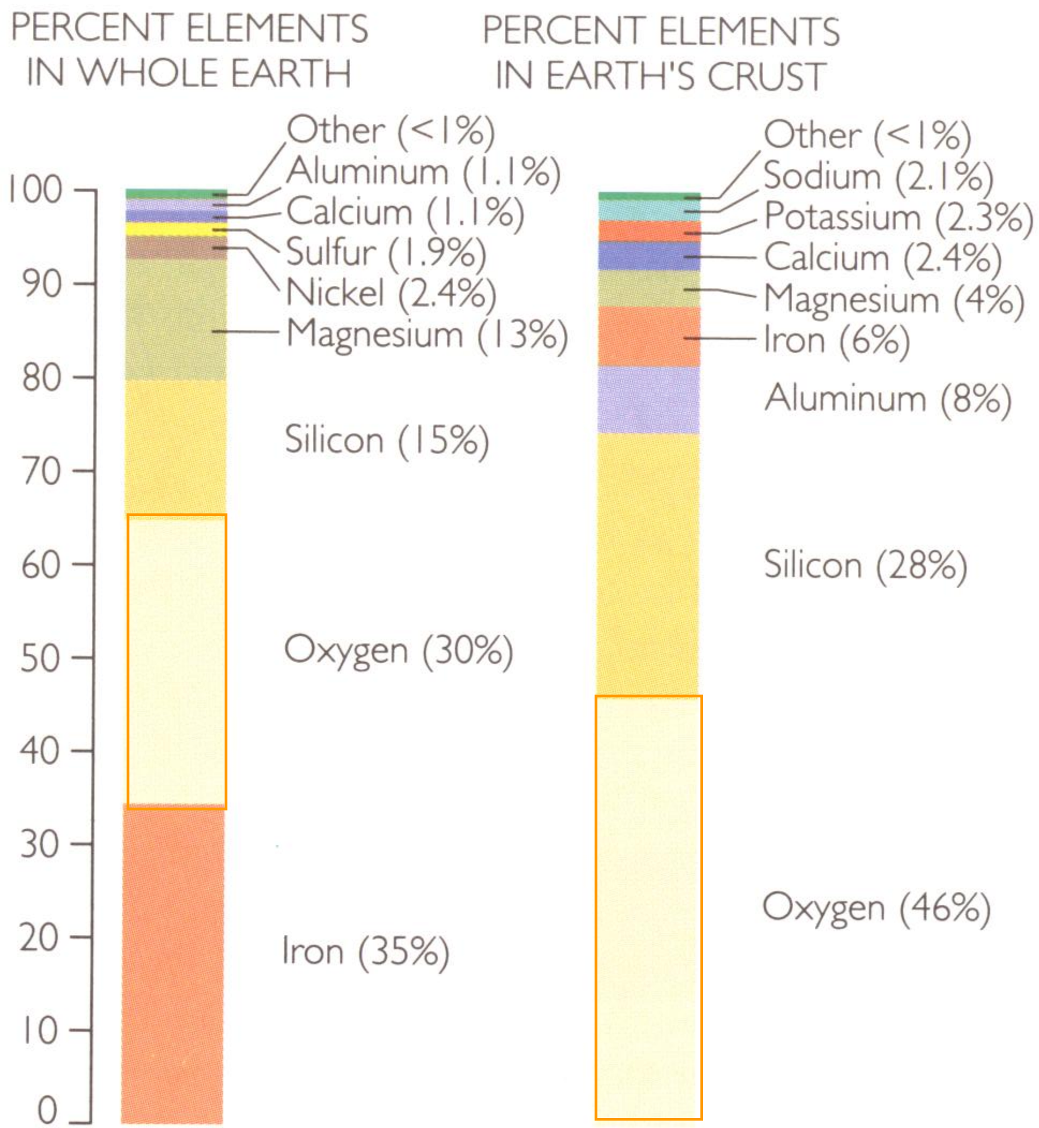


Heat flows outward from Earth's interior. The crust insulates us from Earth's interior heat. The mantle is semi-molten, the outer core is liquid and the inner core is solid.

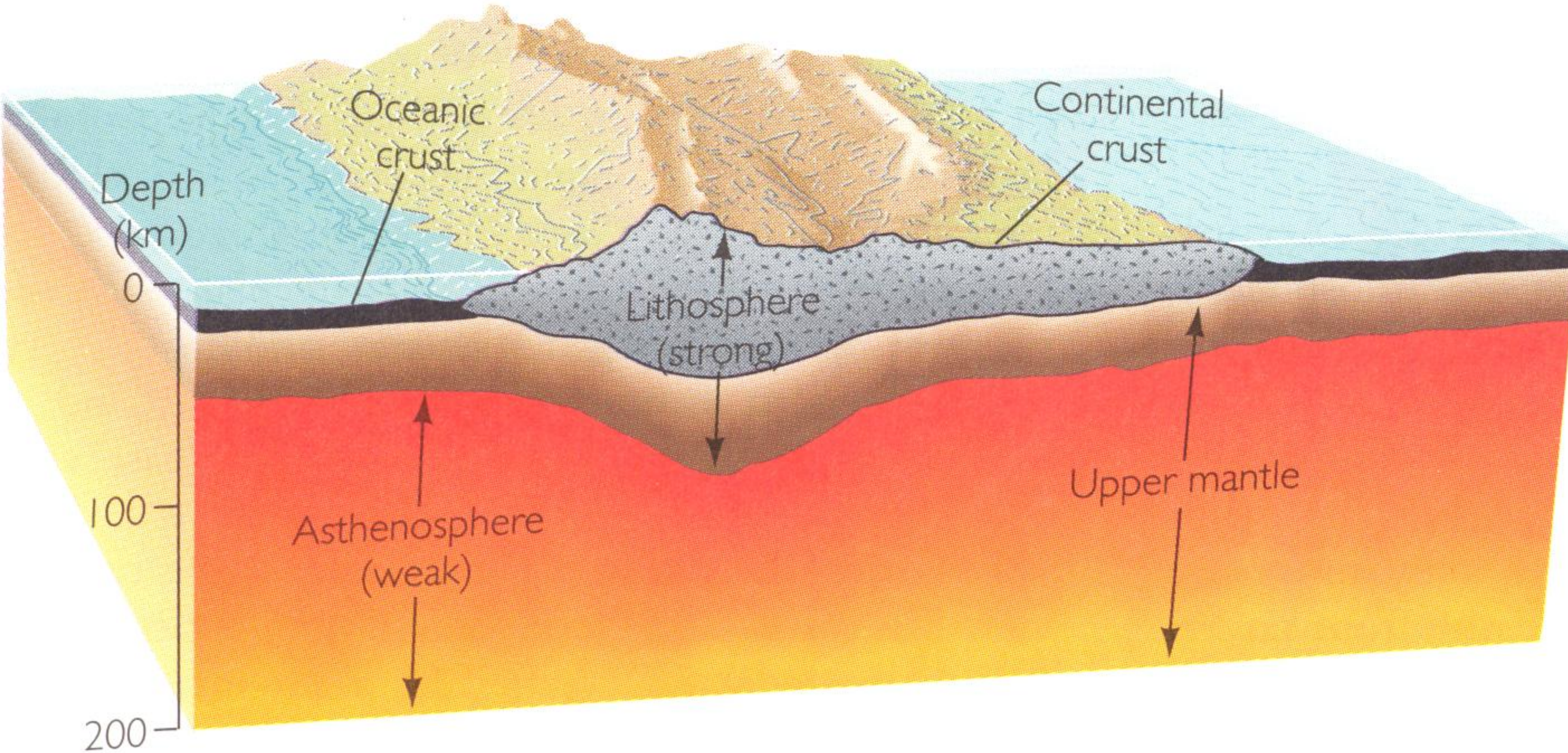
Temperatures in the Earth



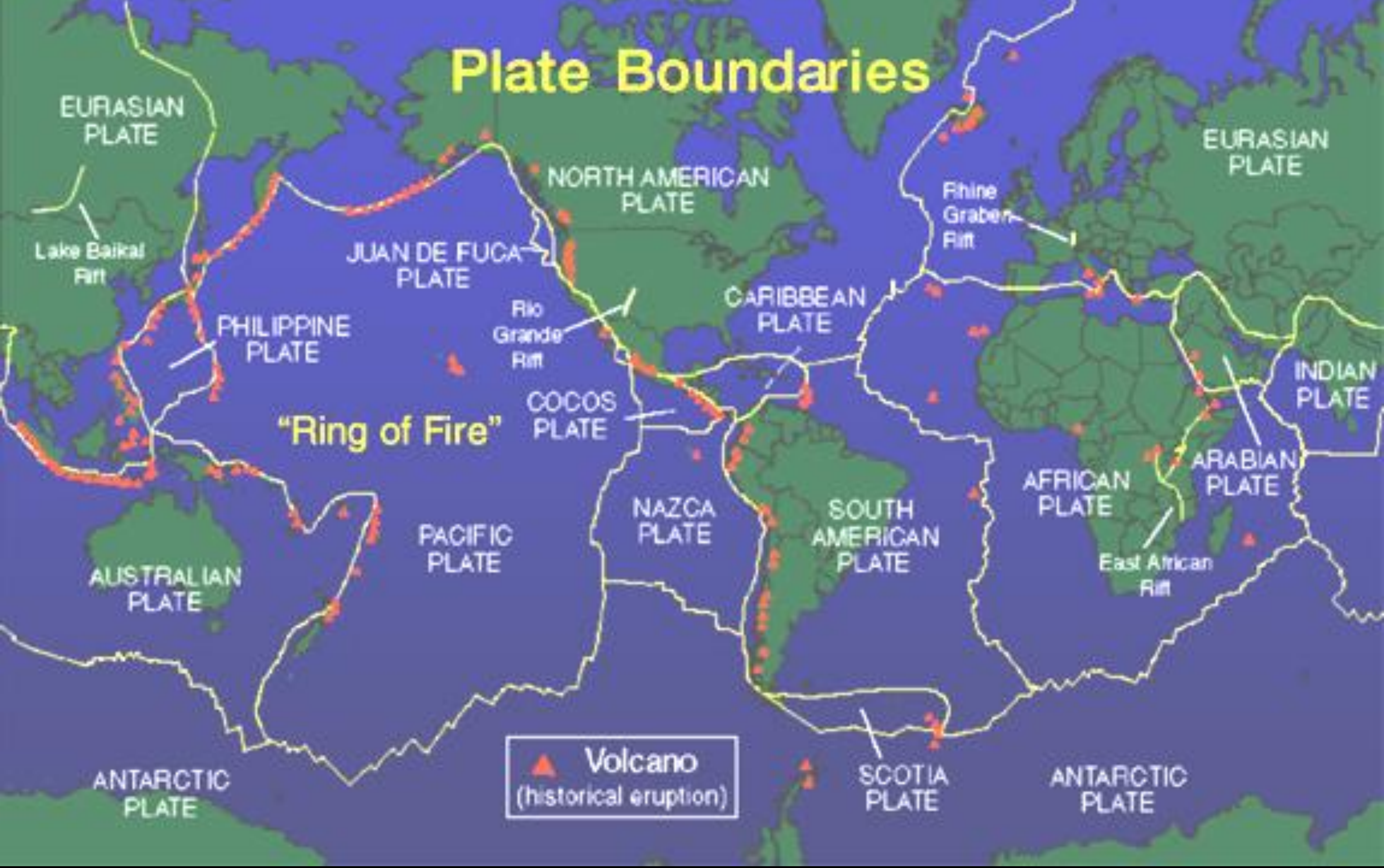
Relative abundance by weight of elements in the whole Earth and in its crust



Differentiation has created a light crust depleted of iron and rich in oxygen, silicon, aluminium, calcium, potassium and sodium.



The Earth's outermost shell is the strong, solid **lithosphere**, composed of the **crust** and **top mantle**. It rides on a weak, partially molten region of the mantle called the **asthenosphere**.



Earth's crust is broken into huge plates that move apart or push together at about the rate our fingernails grow. Convection of semi-molten rock in the upper mantle helps drive plate tectonics.

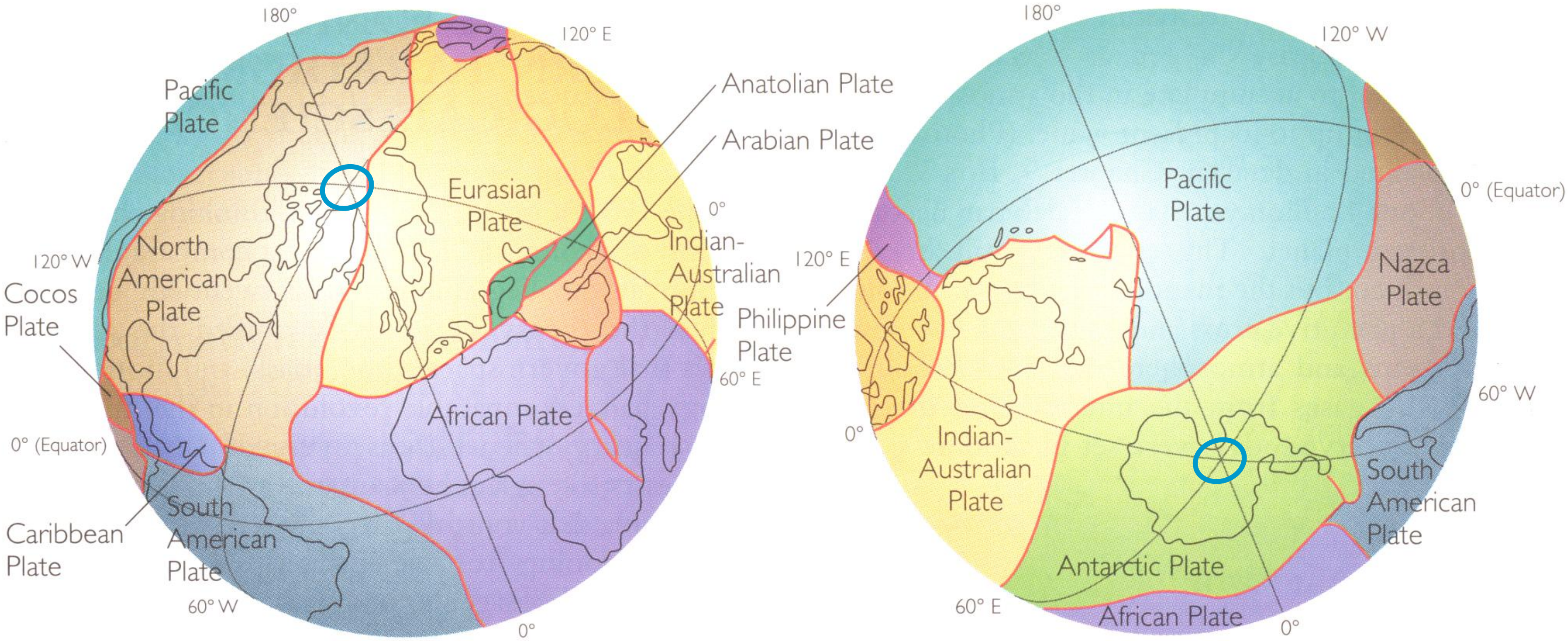
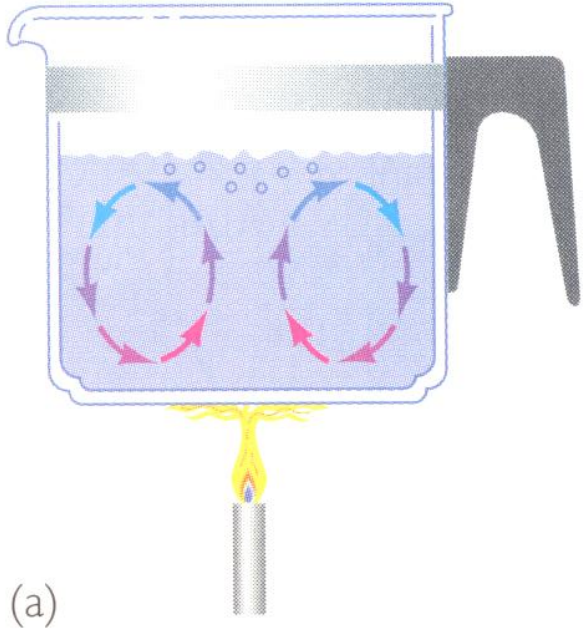
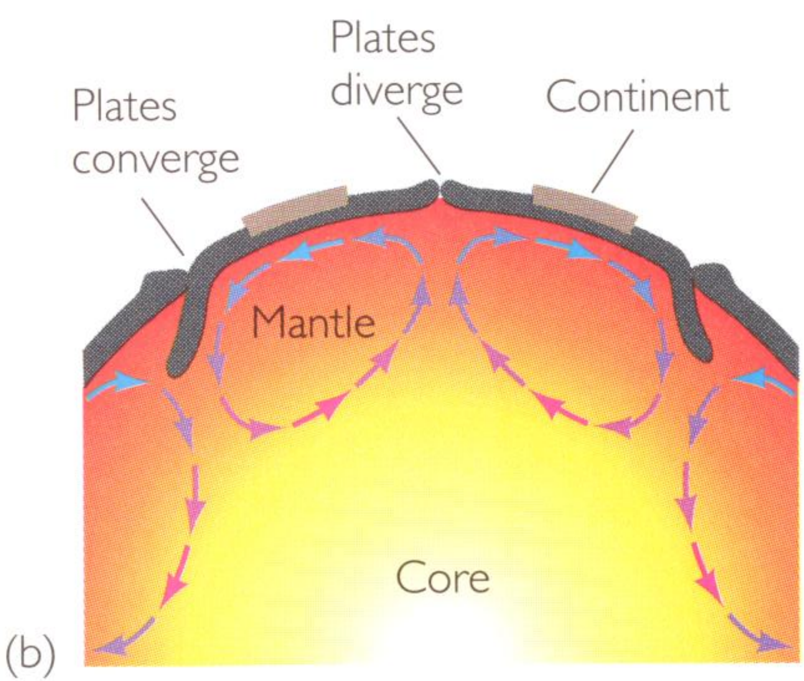


Plate boundaries – where plates separate, collide or slide past each other – are shown by red lines.

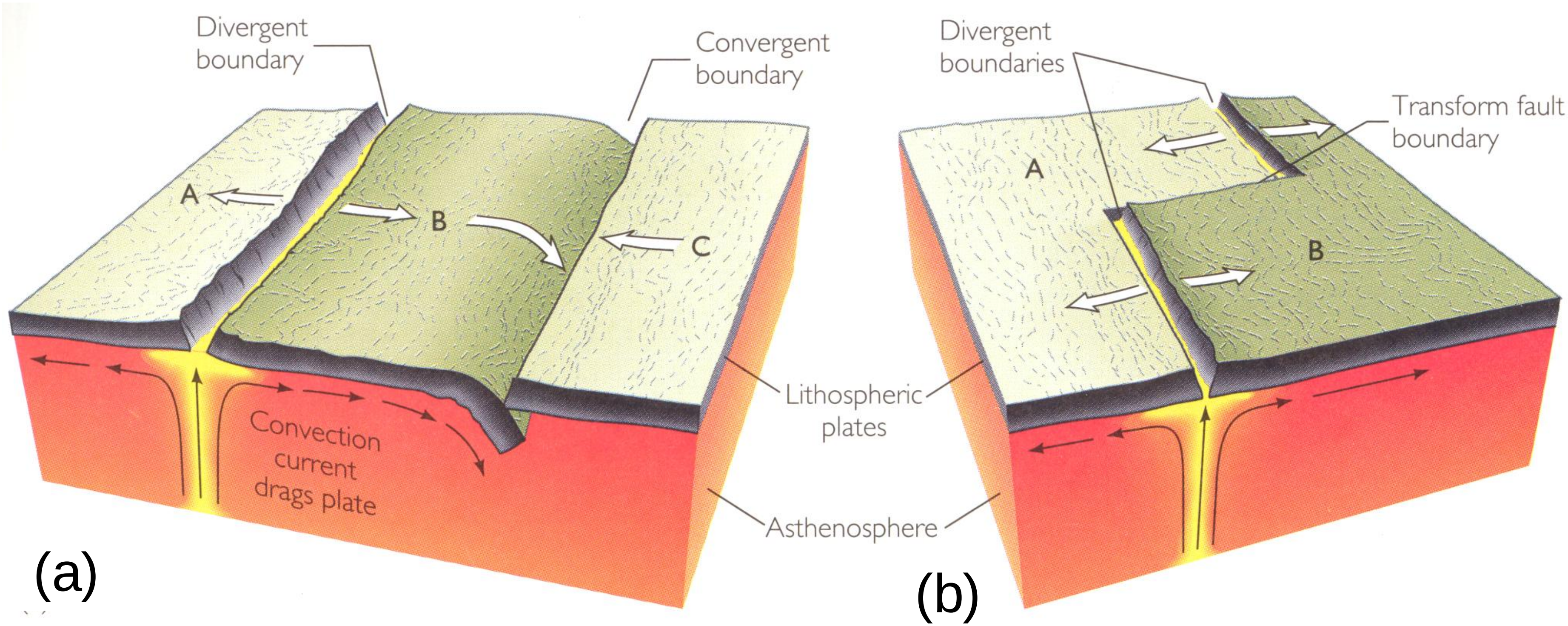




Convection currents in the deep interior are the driving force of plate movements.

Hot matter rises under the plate boundaries and flows in opposite directions, dragging the plates along and forcing them to separate.

At other plate boundaries, cooled mater sinks, tending to drag the plate down.



The three types of plate boundaries:

(a) a **divergent boundary**, where plates A and B separate, and a **convergent boundary**, where plates B and C collide;

(b) a **transform fault boundary**, where plates A and B slip past each other.

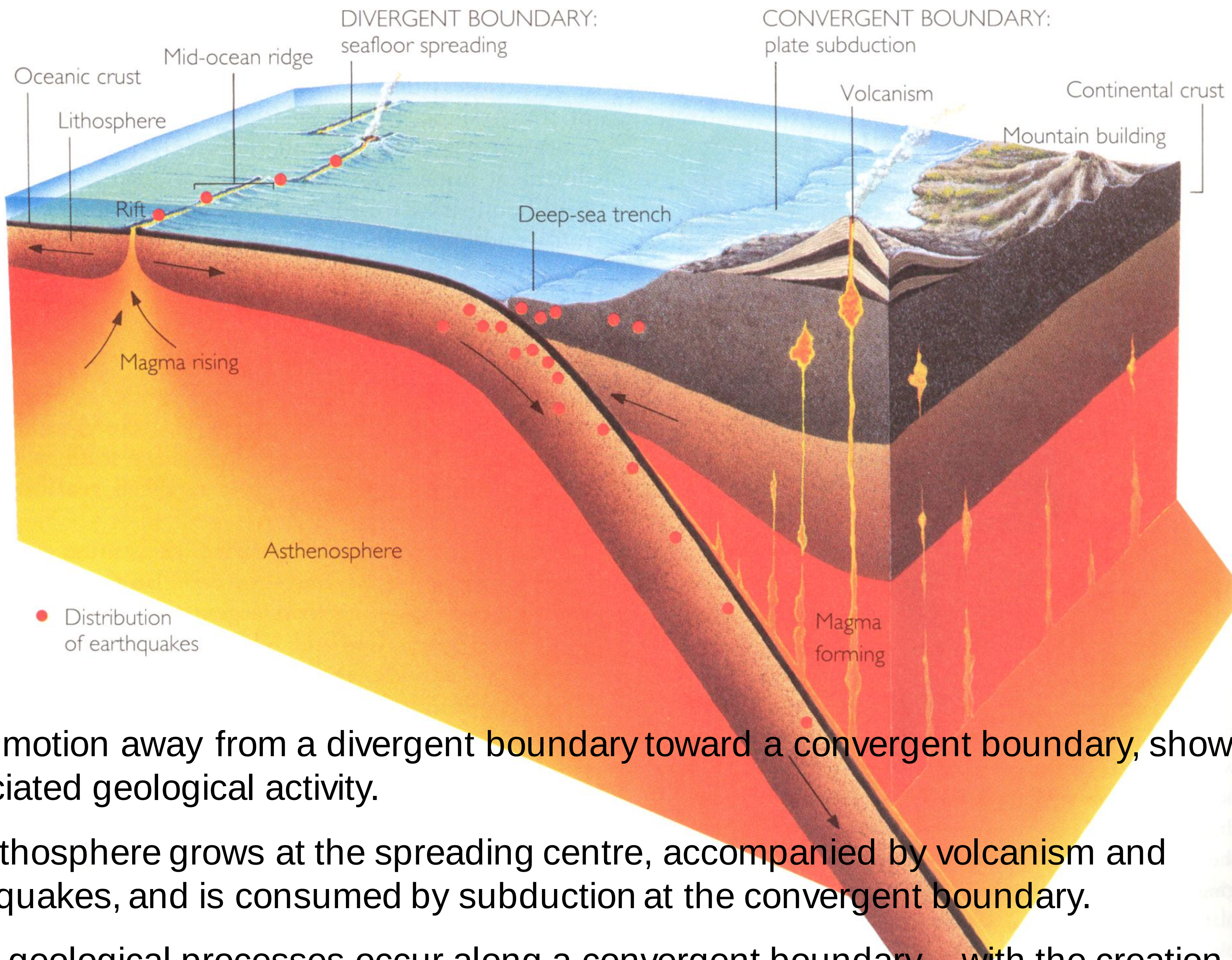
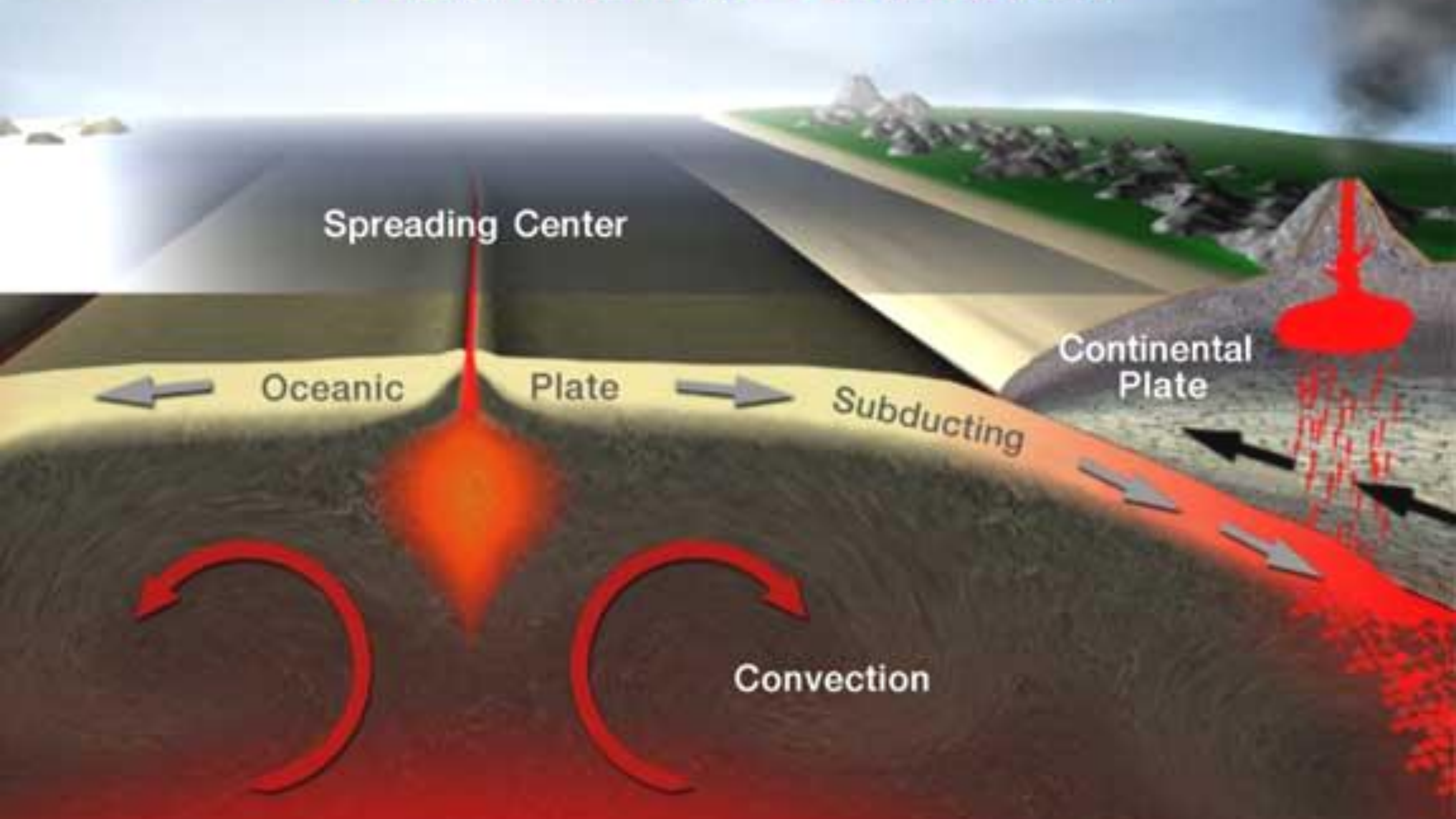


Plate motion away from a divergent boundary toward a convergent boundary, showing associated geological activity.

The lithosphere grows at the spreading centre, accompanied by volcanism and earthquakes, and is consumed by subduction at the convergent boundary.

Many geological processes occur along a convergent boundary – with the creation and upwelling of magma, volcanism, mountain building, creation of a deep-sea trench, and earthquakes.

Plate Tectonic Processes



New crust forms along mid-ocean spreading centers and continental rift zones. When plates meet, one can slide beneath another. Plumes of magma rise from the edges of sinking plates.

Thinned or fractured crust allows magma to rise to the surface as lava. Most magma doesn't reach the surface but heats large regions of underground rock.

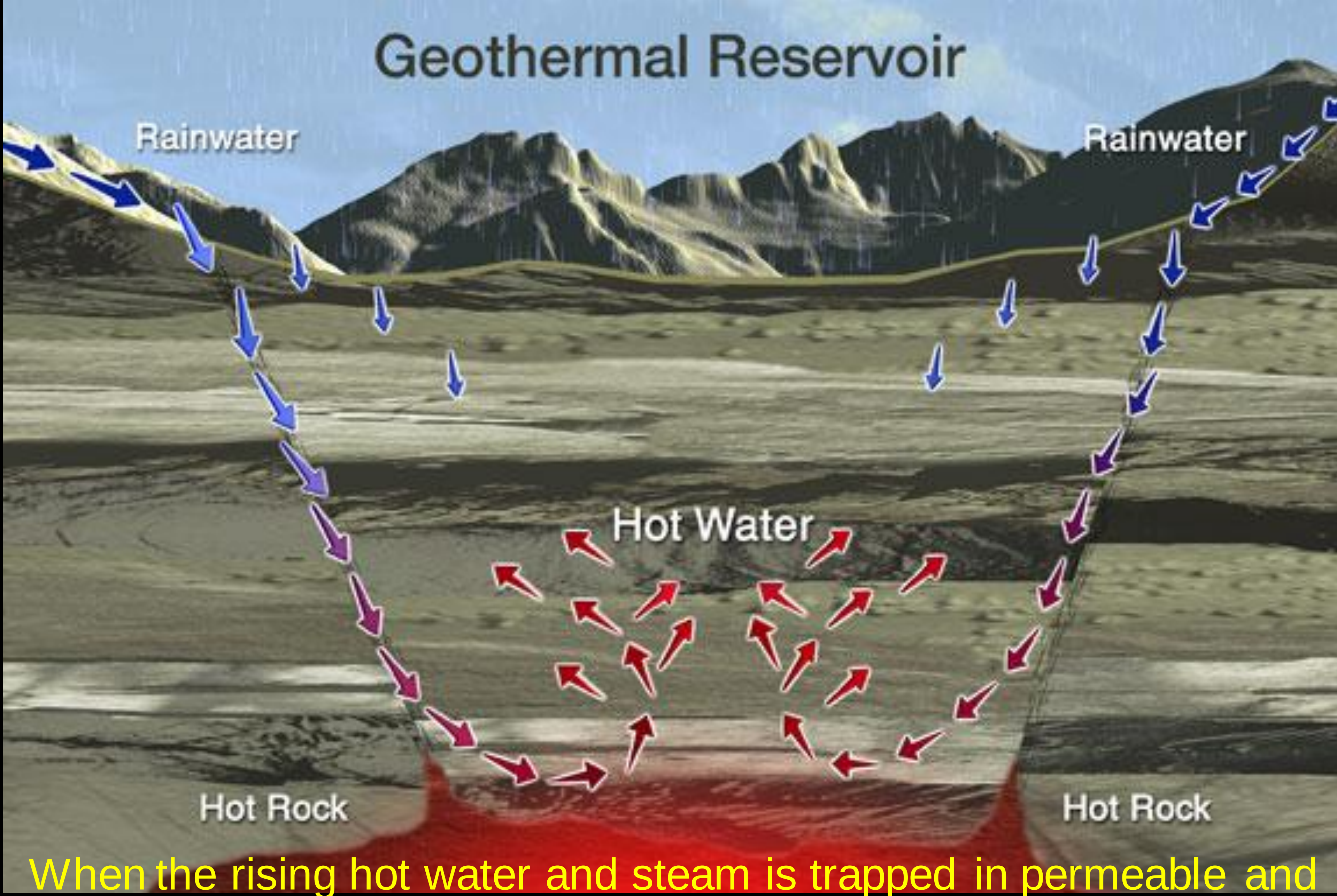
In most places, the temperature rise with depth is fairly constant, typically 3°C per 100 m.

However, there are anomalous regions associated with **volcanic or tectonic activity,** where the temperature gradients far exceed these normal values. For example, in Larderello, Italy, the gradient is 10-30 times greater than normal: temperatures over 300°C can be found at depth of 1 km, easily reachable with today's drilling technology.

If fluids at such high temperatures can be brought to the surface through wells, they can serve as the working fluids for electric generating stations. Such fluids are complex mixtures of high-pressure mineral-laden water, with gases dissolved into solution as a result of contact of the very hot water with various types of rocks in the reservoir.

It is the challenge of geothermal scientists and engineers to locate these reservoirs of hot fluids, design means to bring them to the surface in an economic and reliable fashion, process them in a suitable power plant to generate electricity, and then to dispose of the spent fluid in an environmentally acceptable manner, usually by returning the fluid to the reservoir through injection wells.

Rainwater can seep down faults and fractured rocks for kms. After being heated, it can return to the surface as steam or hot water.

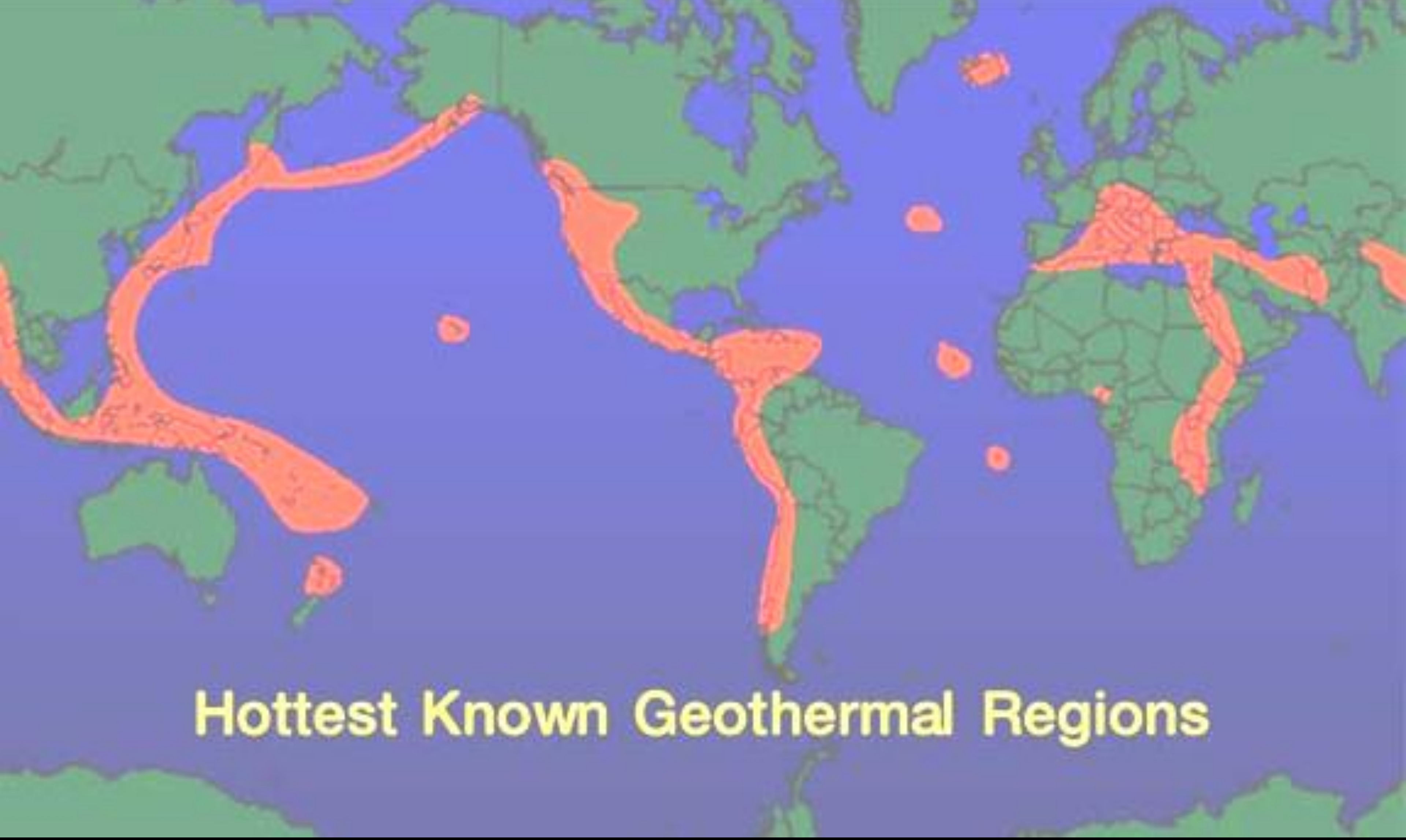


When the rising hot water and steam is trapped in permeable and porous rocks under a layer of impermeable rock, it can form a geothermal reservoir.

Powerful Energy Source

- Geothermal reservoirs can reach temperatures of 370ºC.

- A geothermal reservoir is a powerful source of energy!



Many areas have accessible geothermal resources, especially countries along the circum-Pacific "Ring of Fire," spreading centres, continental rift zones and other hot spots.

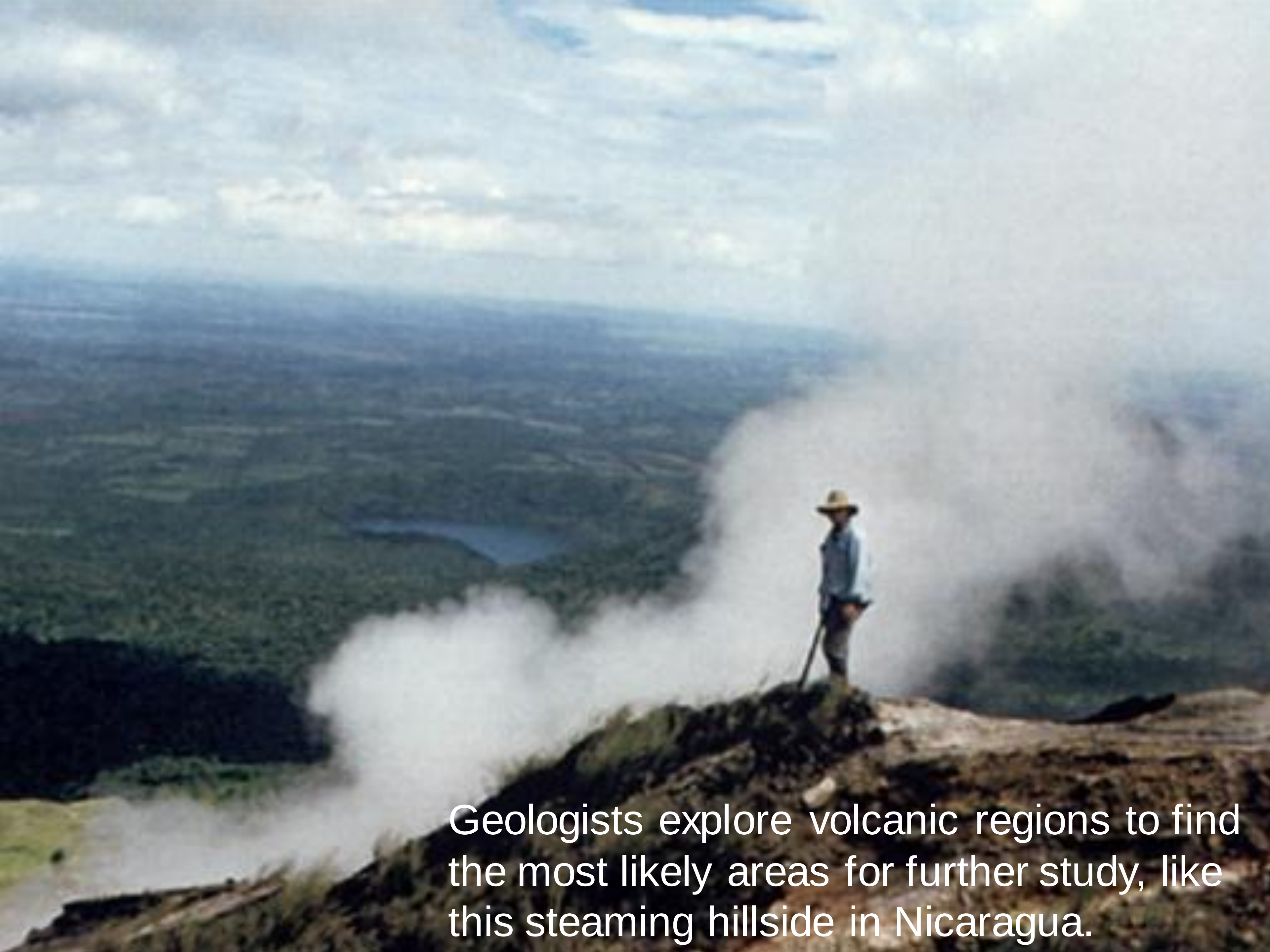
Geothermal Exploration Surveys

- Satellite imagery and aerial photography
- Volcanological studies
- Geologic and structural mapping
- Geochemical surveys
- Geophysical surveys
- Temperature gradient hole drilling

These and other methods are used.

Exploration commonly begins with analysis of satellite images and aerial photographs.

Volcanoes are obvious indications of underground heat.



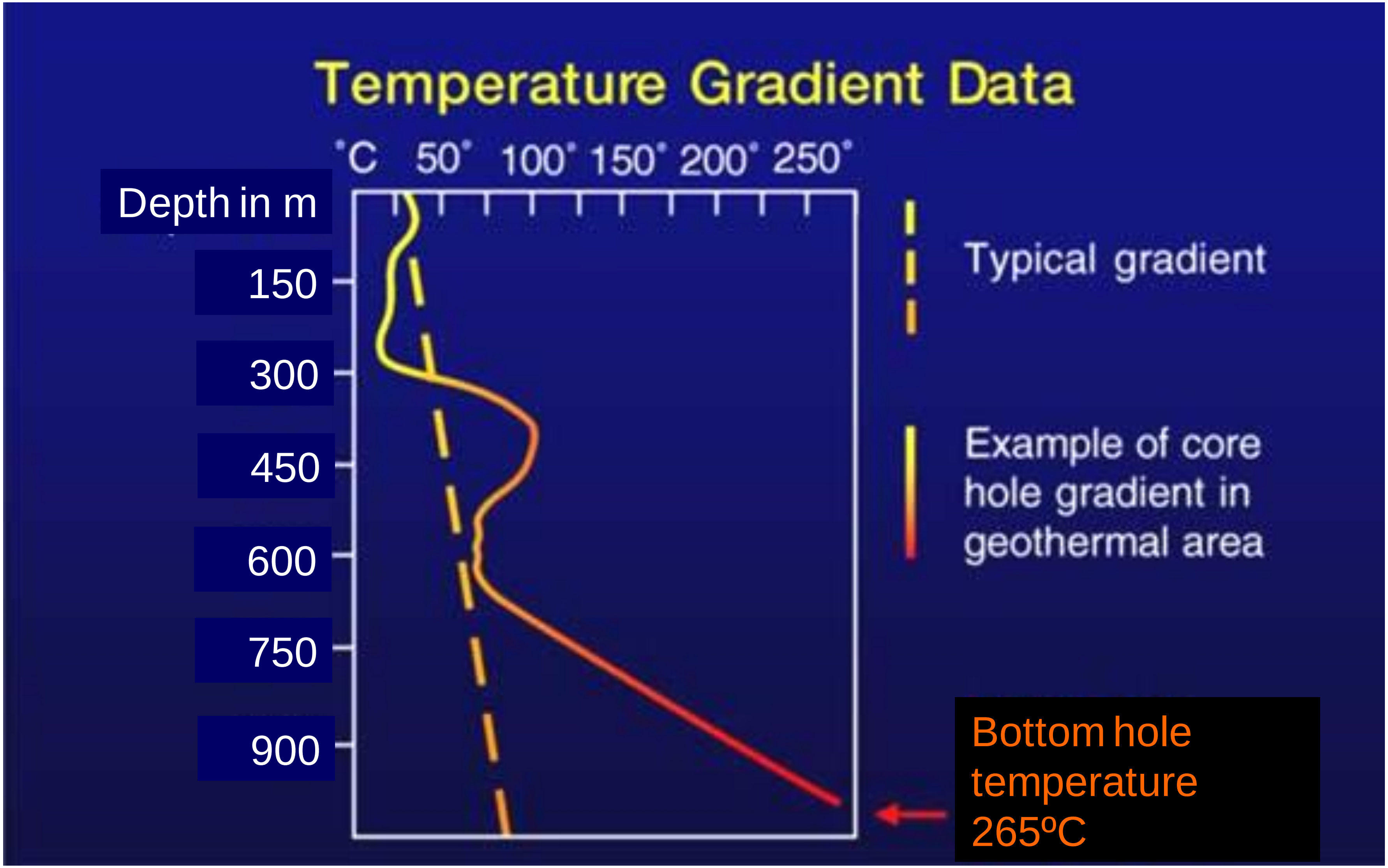
Geologists explore volcanic regions to find the most likely areas for further study, like this steaming hillside in Nicaragua.

Data from electrical, magnetic, chemical and seismic surveys is gathered in the field.

Geologists and drillers study the data to decide whether to recommend drilling. Geothermal reservoirs suitable for commercial use can only be discovered by drilling.

First, a small- diameter "temperature gradient hole" is drilled (some only 60 m deep, some over 1200 m deep) with a truck-mounted rig to determine the temperatures and underground rock types.

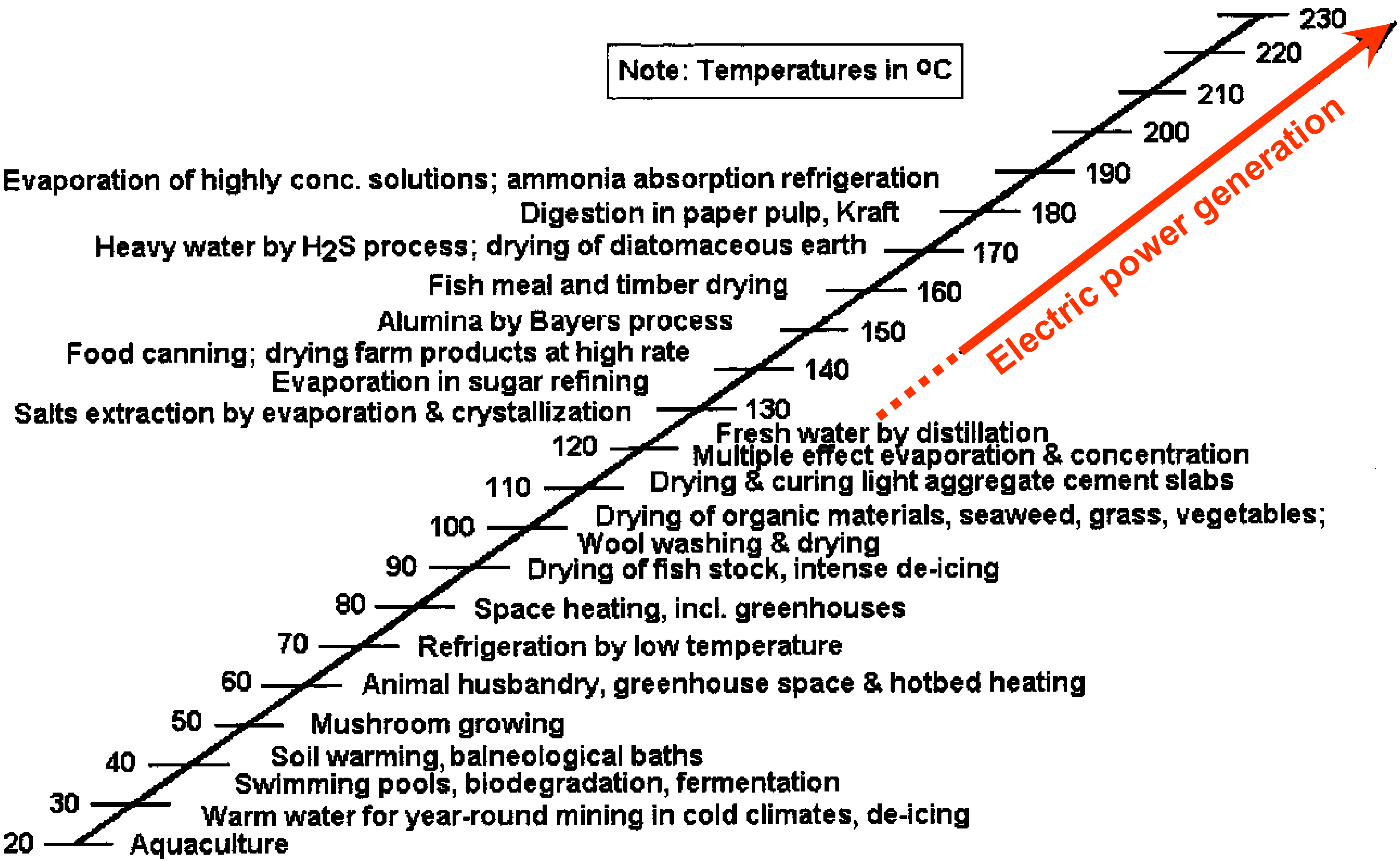
Geologists examine the cored rock (shown here marked with depth markers).



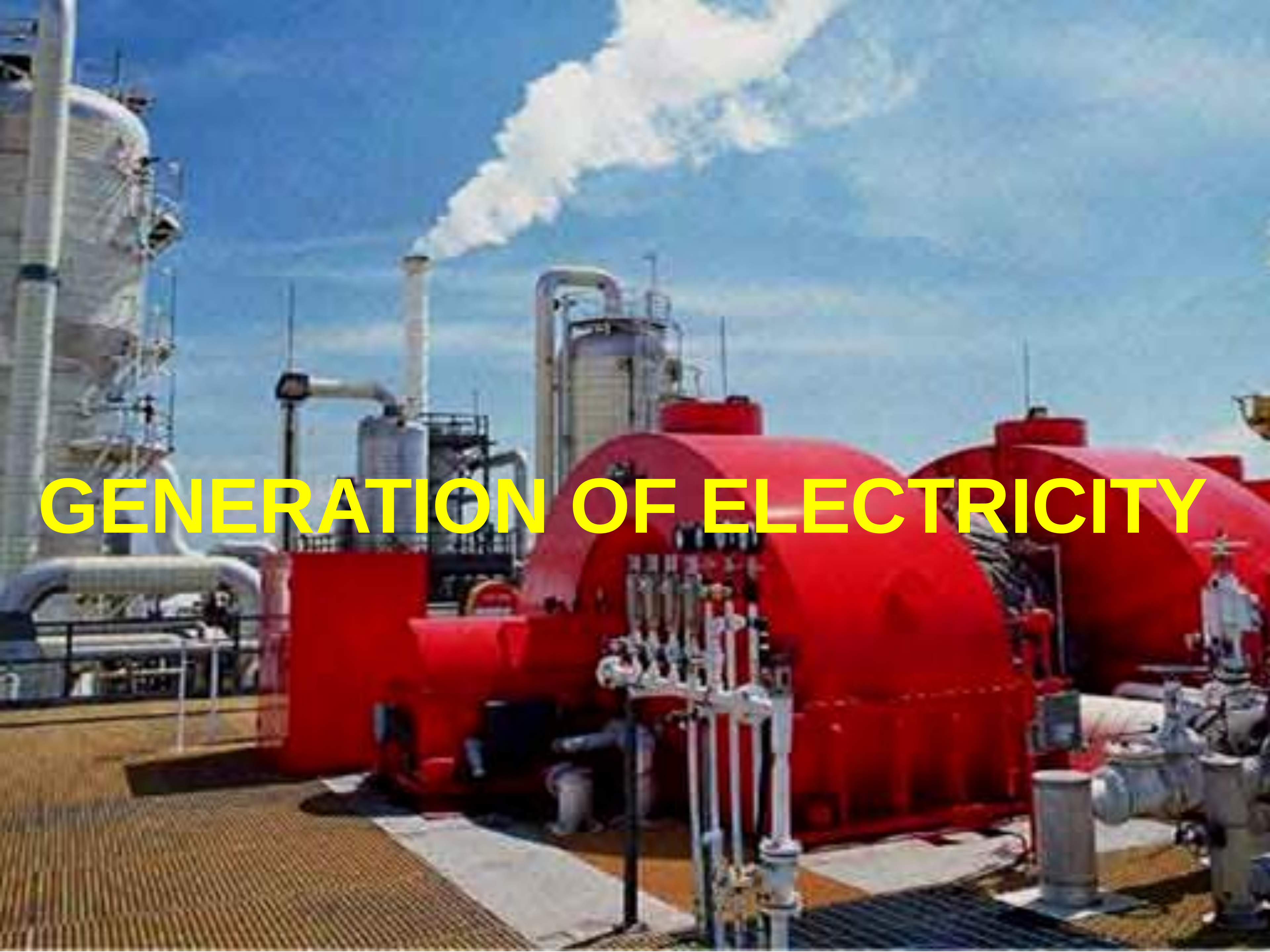
Temperature results like this would definitely encourage the drilling of a larger, deeper well to try to find a hydrothermal reservoir.

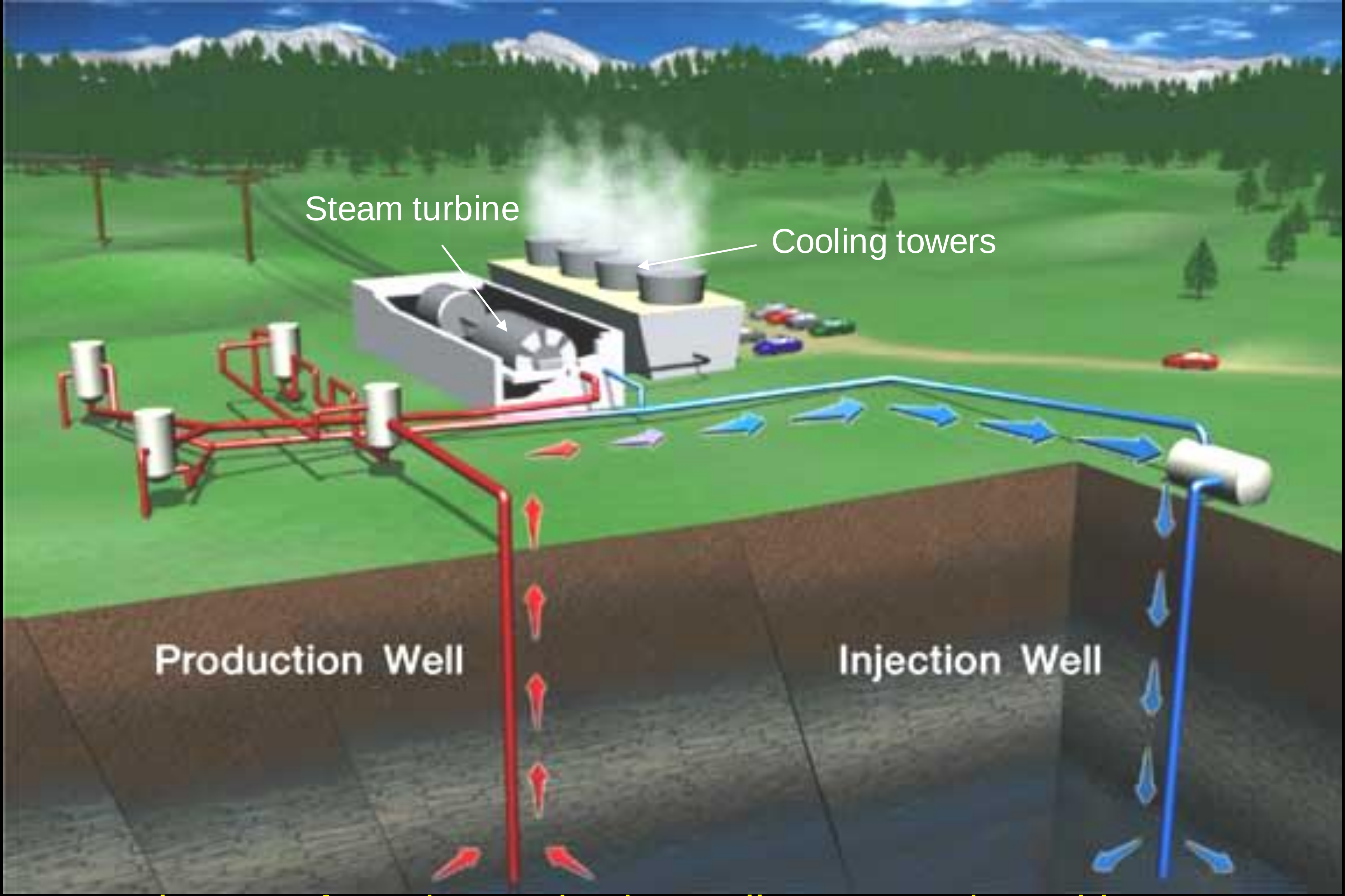
Production-sized wells require large drill rigs like these and can cost as much as a million dollars or more to drill. Geothermal wells can be drilled over 3 km deep.

Applications for geothermal fluids

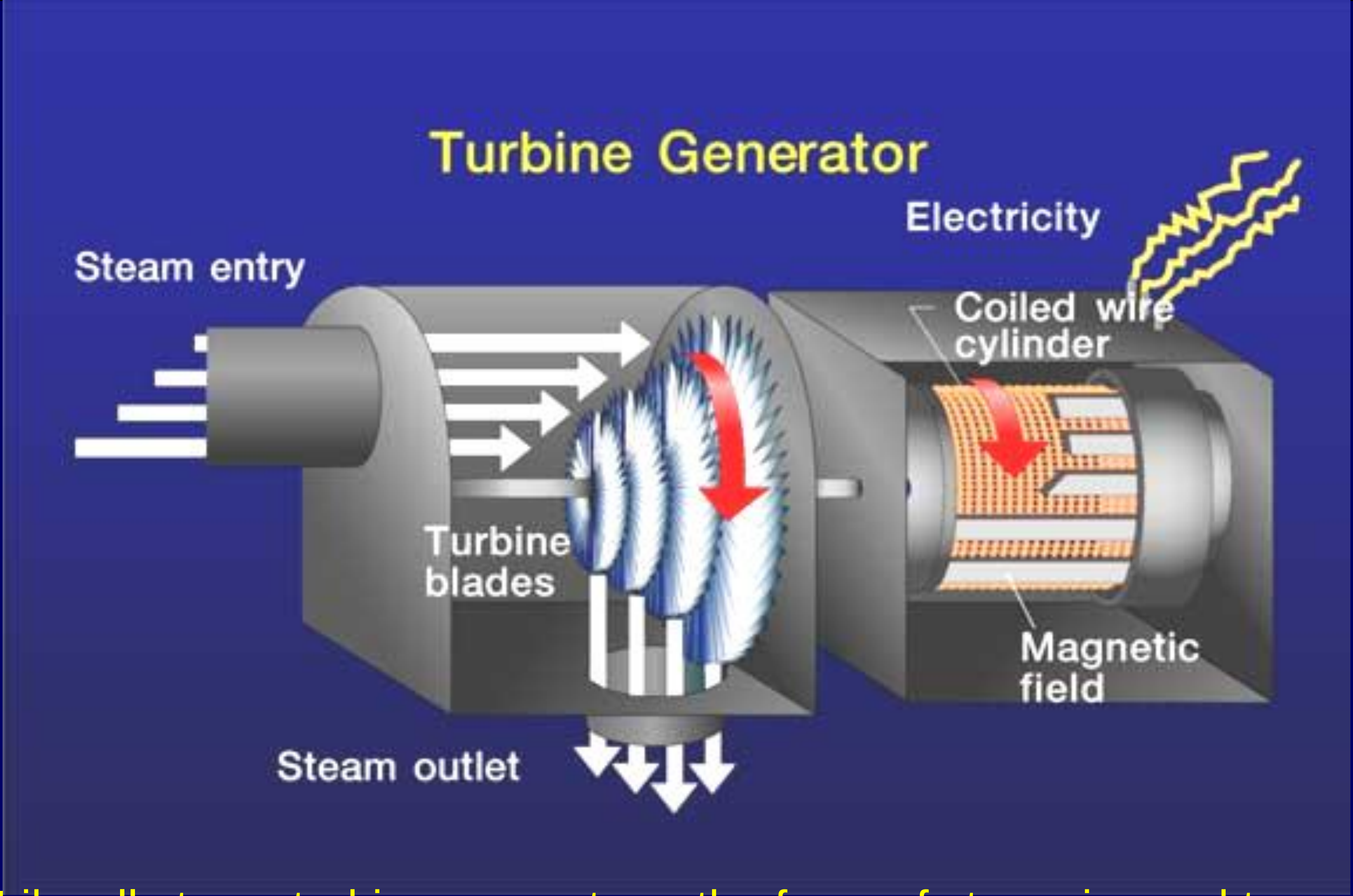


GENERATION OF ELECTRICITY





Natural steam, from the production wells, powers the turbine generator. The steam is condensed by evaporation in the cooling tower and pumped down an injection well to sustain production.

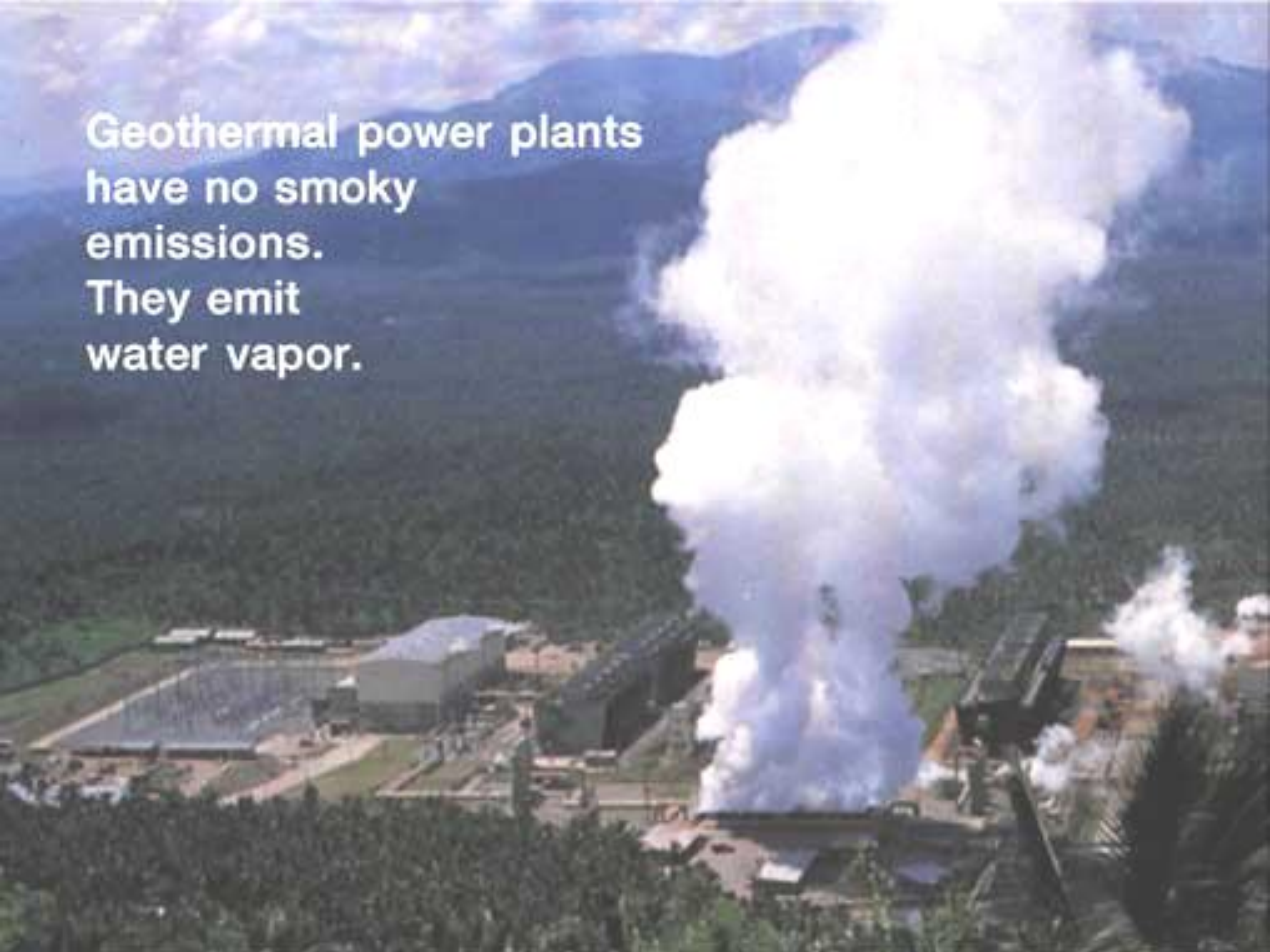


Like all steam turbine generators, the force of steam is used to spin the turbine blades which spin the generator, producing electricity. But with geothermal energy, no fuels are burned.

Turbine generator outdoors at an Imperial Valley geothermal power plant in California.

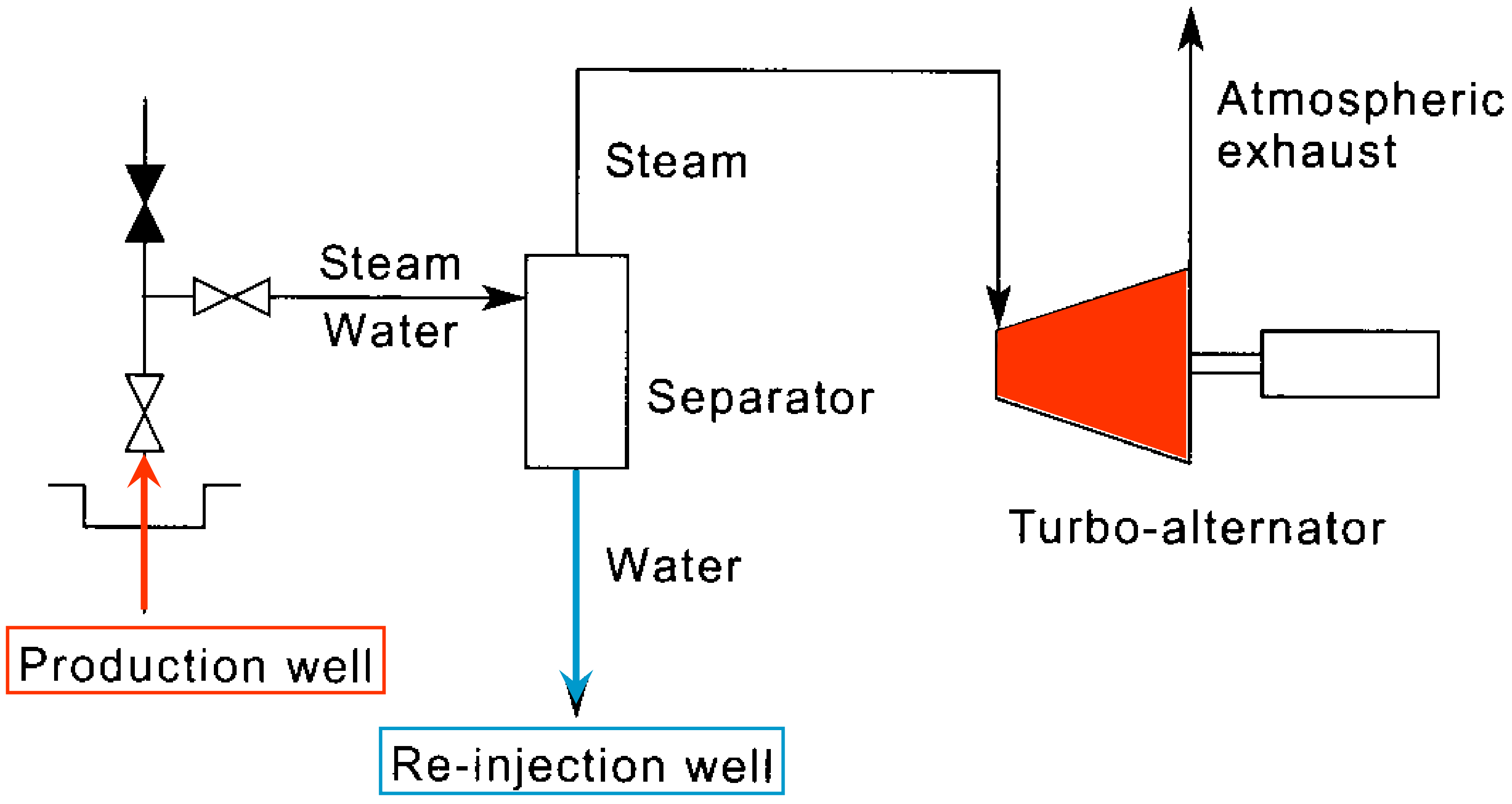
Turbine rotor blades inside a geothermal turbine generator. These turbines are similar to steam turbines of conventional plants.

Turbine generator in a geothermal power plant in Cerro Prieto, Mexico.

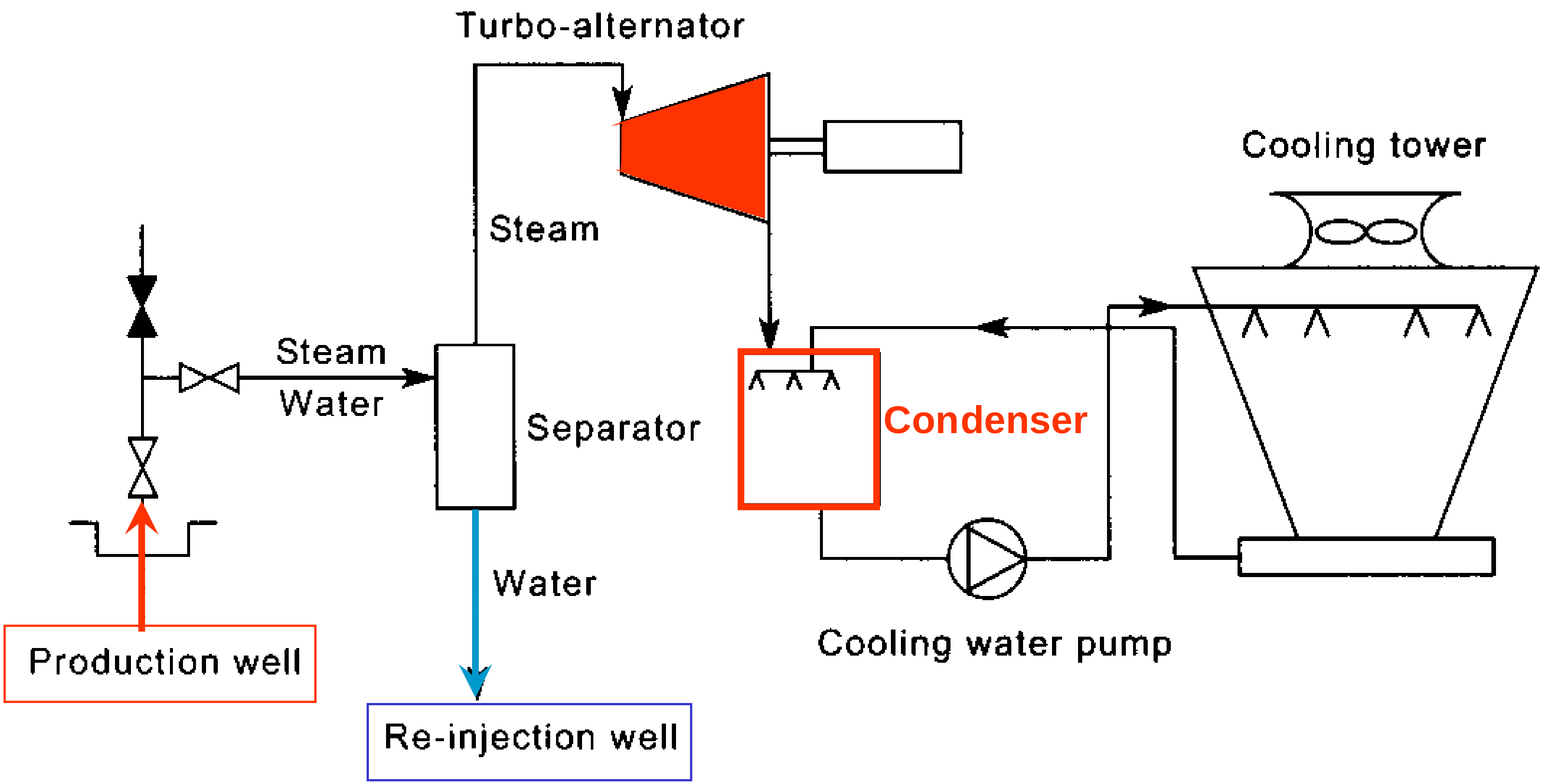

Geothermal power plants
have no smoky
emissions.
They emit
water vapor.

There are different kinds of geothermal reservoirs and different kinds of power plants.

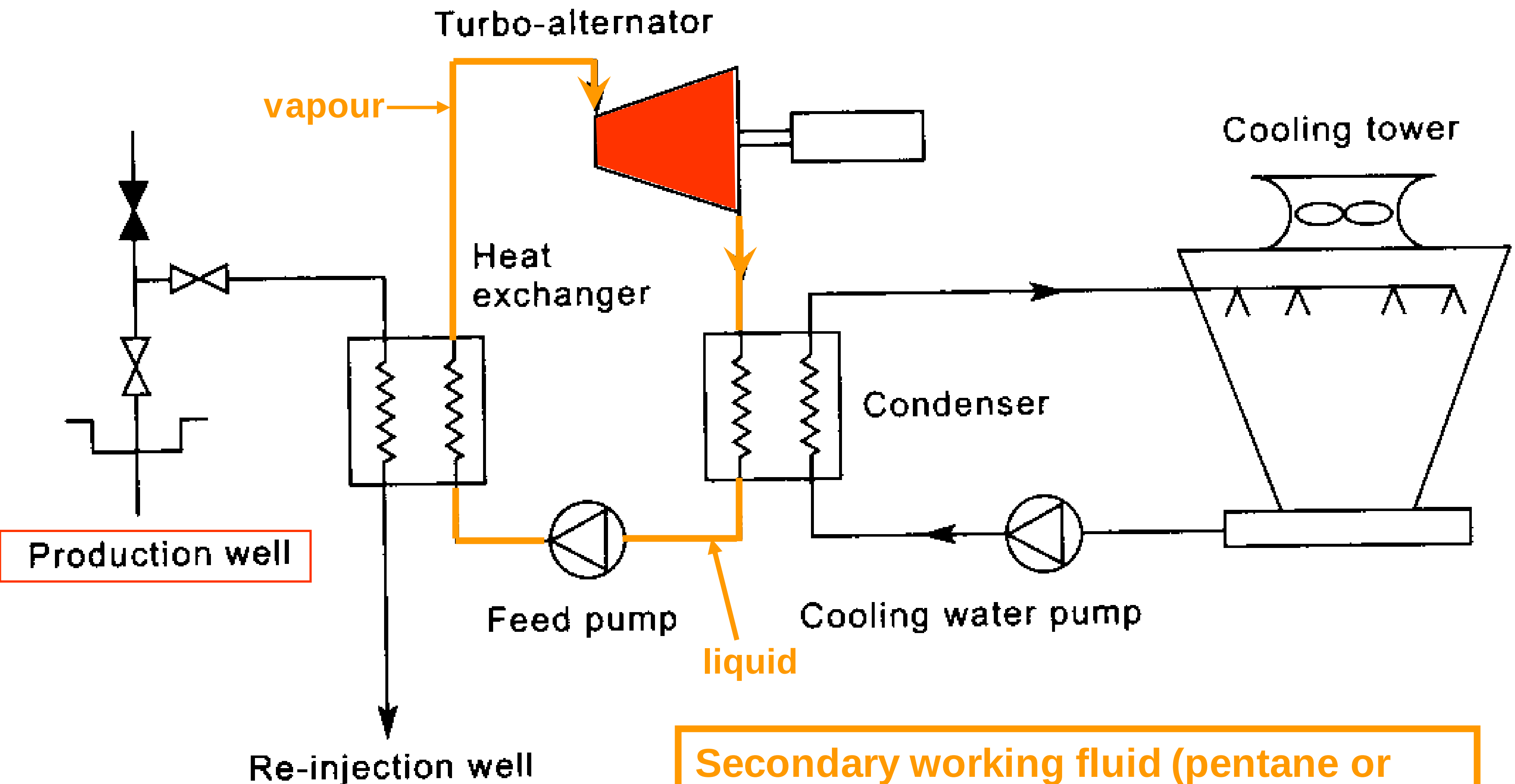
Atmospheric exhaust (no condenser) conventional steam turbine cycle



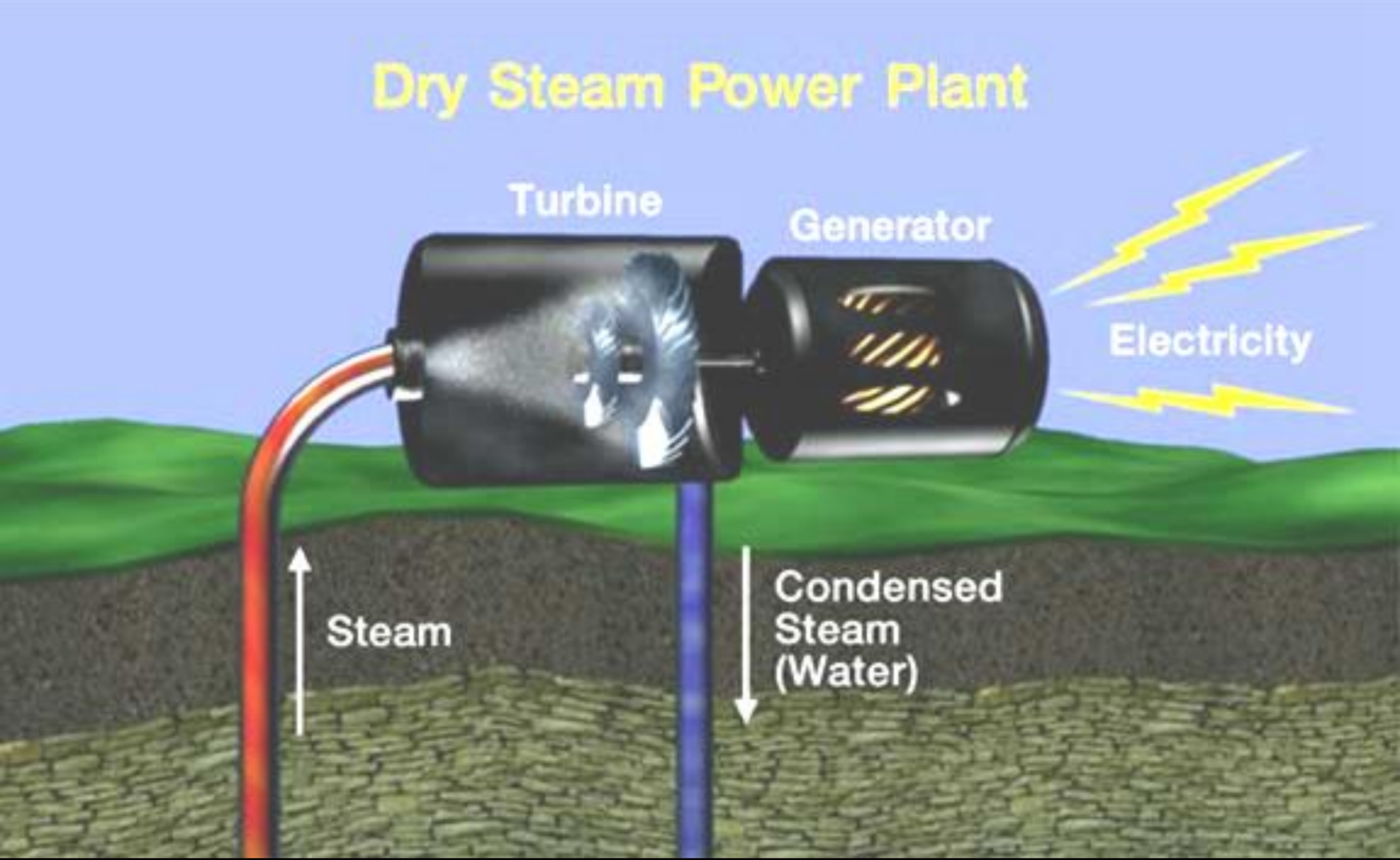
Condensing steam turbine cycle (simplified)



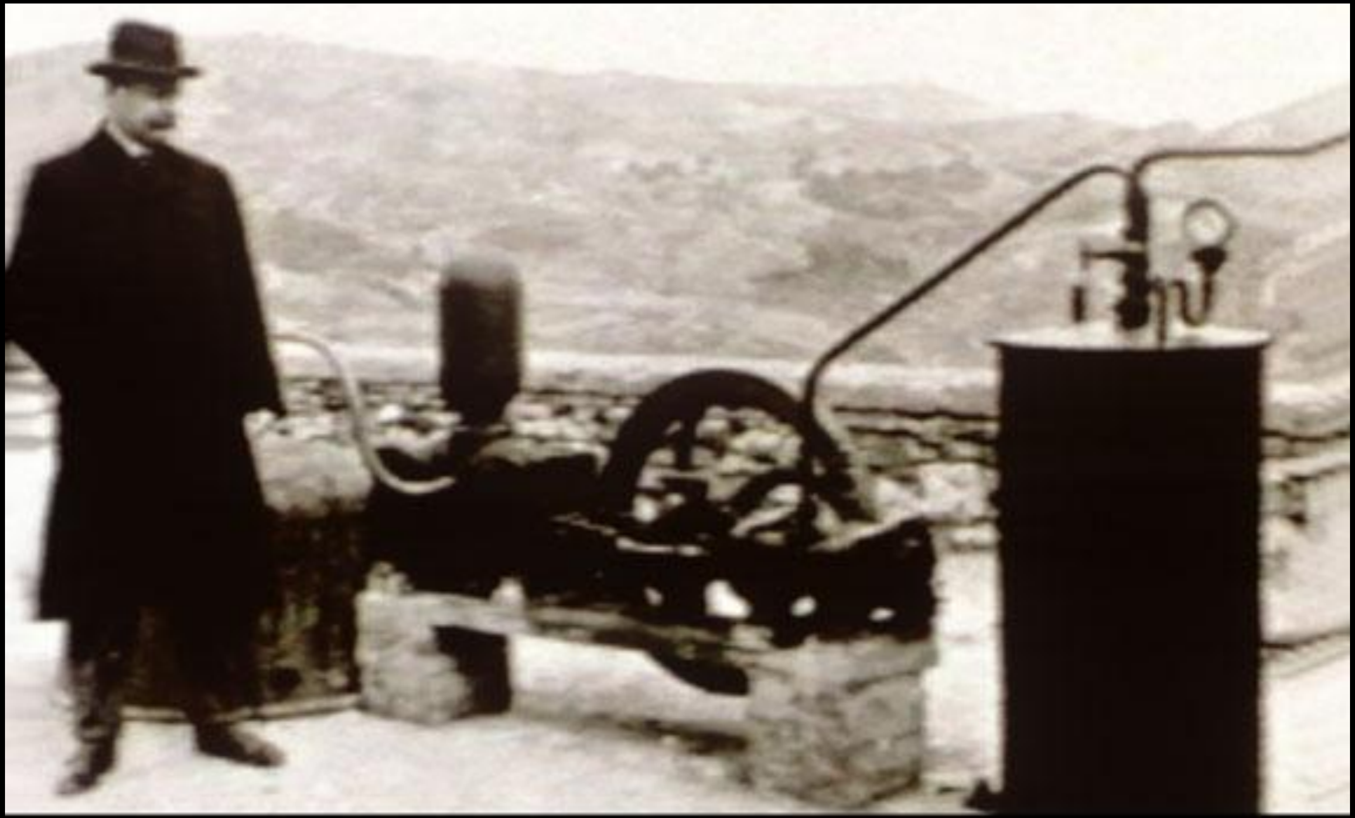
Binary cycle (simplified)



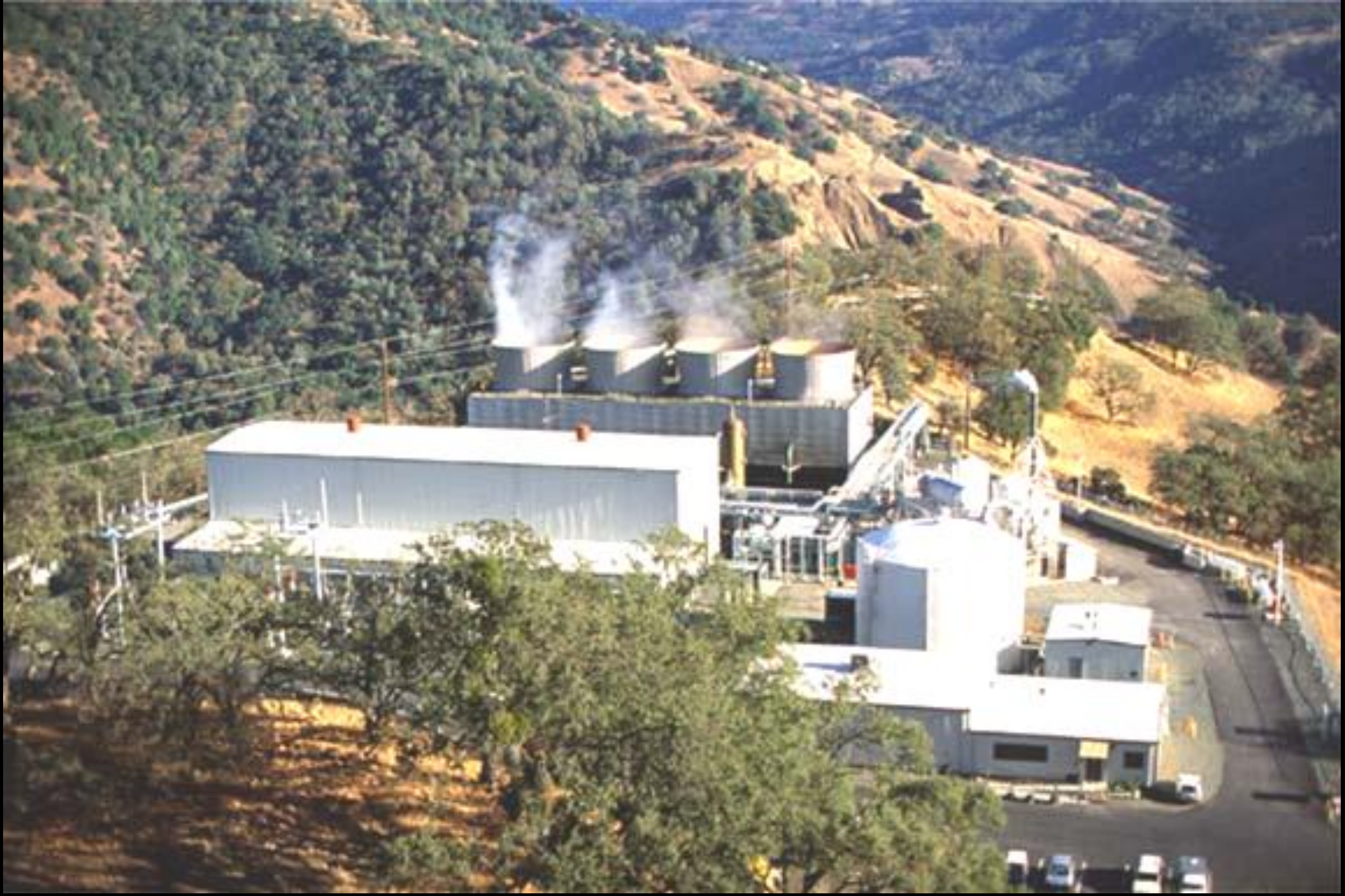
Secondary working fluid (pentane or butane) has a lower boiling point than water.



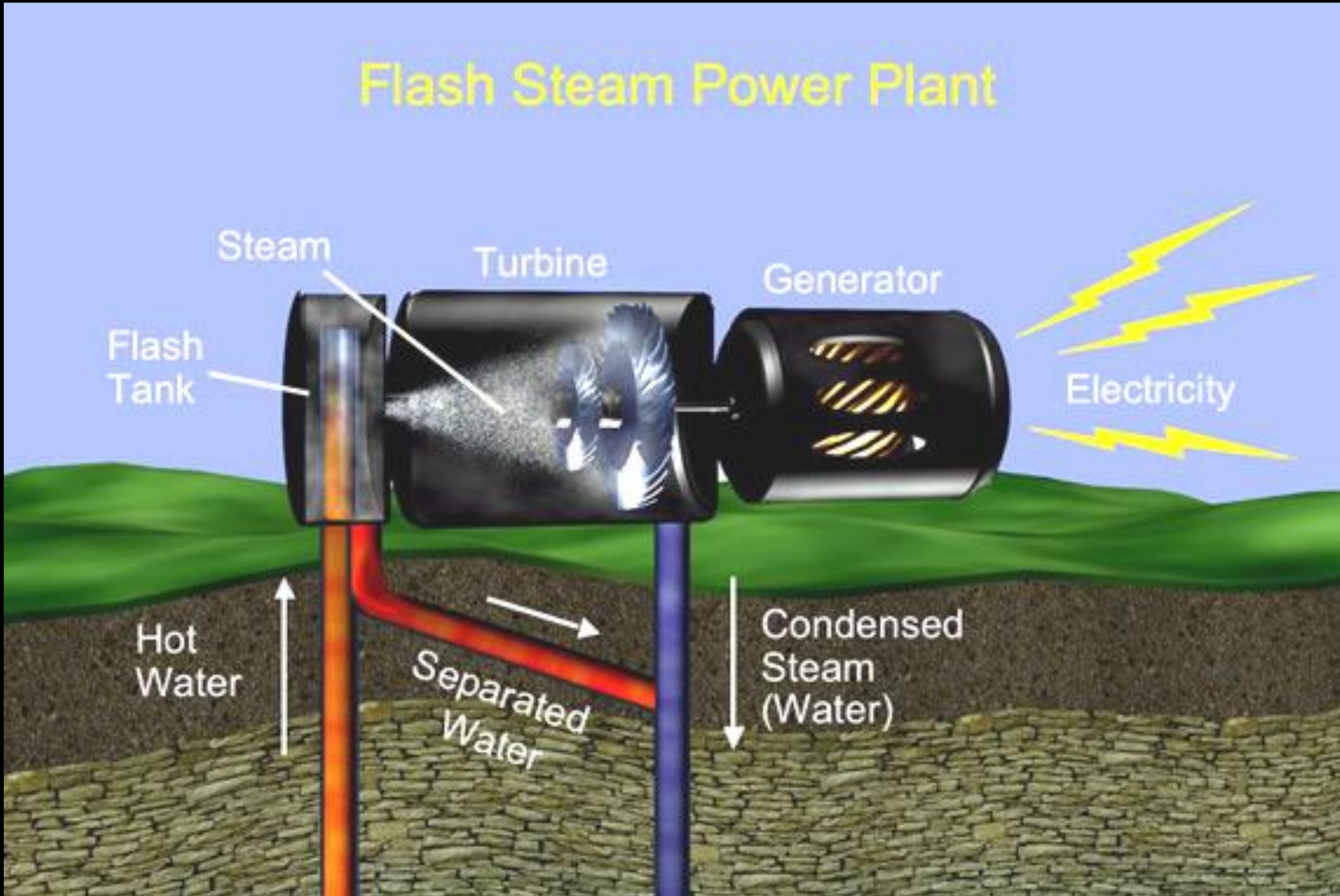
In dry steam power plants, the <u>steam (and no water)</u> shoots up the wells and is passed through a rock catcher (not shown) and then directly into the turbine. Dry steam fields are rare.



Prince Piero Ginori Conti invented the first geothermal power plant in 1904, at the Larderello dry steam field in Italy.



The first geothermal power plants in the U.S. were built in 1962 at The Geysers dry steam field, in northern California. The Geysers is still the largest producing geothermal field in the world.



Flash steam power plants use hot water reservoirs. In flash plants, as hot water is released from the pressure of the deep reservoir in a flash tank, some if it flashes to steam.

The **single-flash steam plant** is the mainstay of the geothermal power industry. As of July 2004, there were 135 units in operation in 18 countries. They account for 29% of all geothermal plants and constitute about 40% of the total geothermal power capacity worldwide. The unit power capacity ranges between 3 and 90 MW (average power per unit: 28 MW).

When the geothermal wells produce a mixture of steam and liquid, the single-flash plant is a simple way to convert the geothermal energy into electricity.

The mixture is separated into distinct steam and liquid phases in a vertical-axis cylindrical cyclonic pressure vessel, where the two phases disengage due to their different densities.

The flash process – transition from a pressurized liquid to a mixture of liquid and vapour as a result of lowering the pressure below the saturation pressure corresponding to the fluid temperature - may occur in a number of places: (1) in the reservoir; (2) in the production well; (3) in the inlet to the cyclone separator as a result of a throttling process induced by a control valve or an orifice plate.

A typical 30 MW single-flash power plant needs 5-6 production wells and 2-3 injection wells.

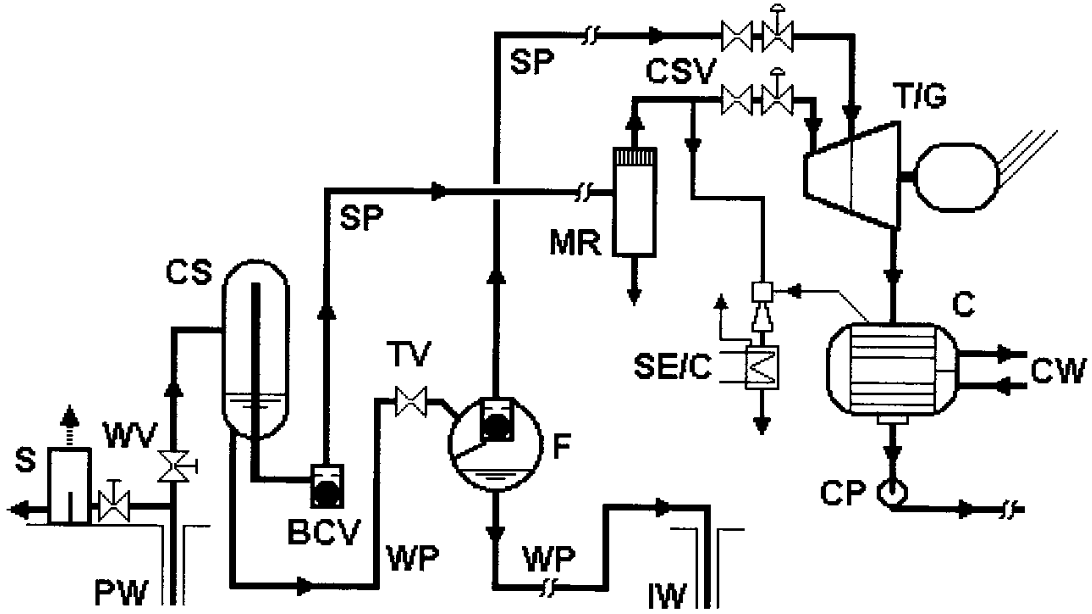
The **double-flash steam plant** is an improvement on the single-flash design in that it can produce 15-25% more power output for the same geothermal fluid conditions. The plant is more complex, more costly and requires more maintenance, but the extra power output often justifies that.

As of mid-2004, there were 70 units, 15% of all geothermal plants. The power capacity ranges from 4.7 to 110 MW, with an average of 30 MW.

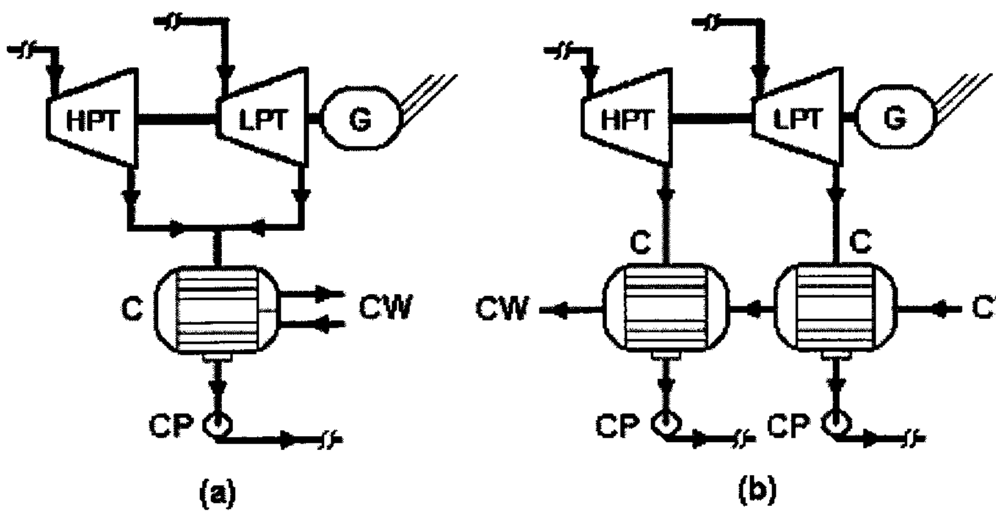
The fundamental new feature is **a second flash process** imposed on the separated liquid leaving the primary separator, in order to generate additional steam, although at a lower pressure than the primary steam.

The secondary low-pressure steam is admitted into a dual-admission turbine at an appropriate stage so as to merge smoothly with the partly expanded high-pressure steam.

An alternative design has two separate turbines: one for the high pressure steam and another one for the low pressure steam.



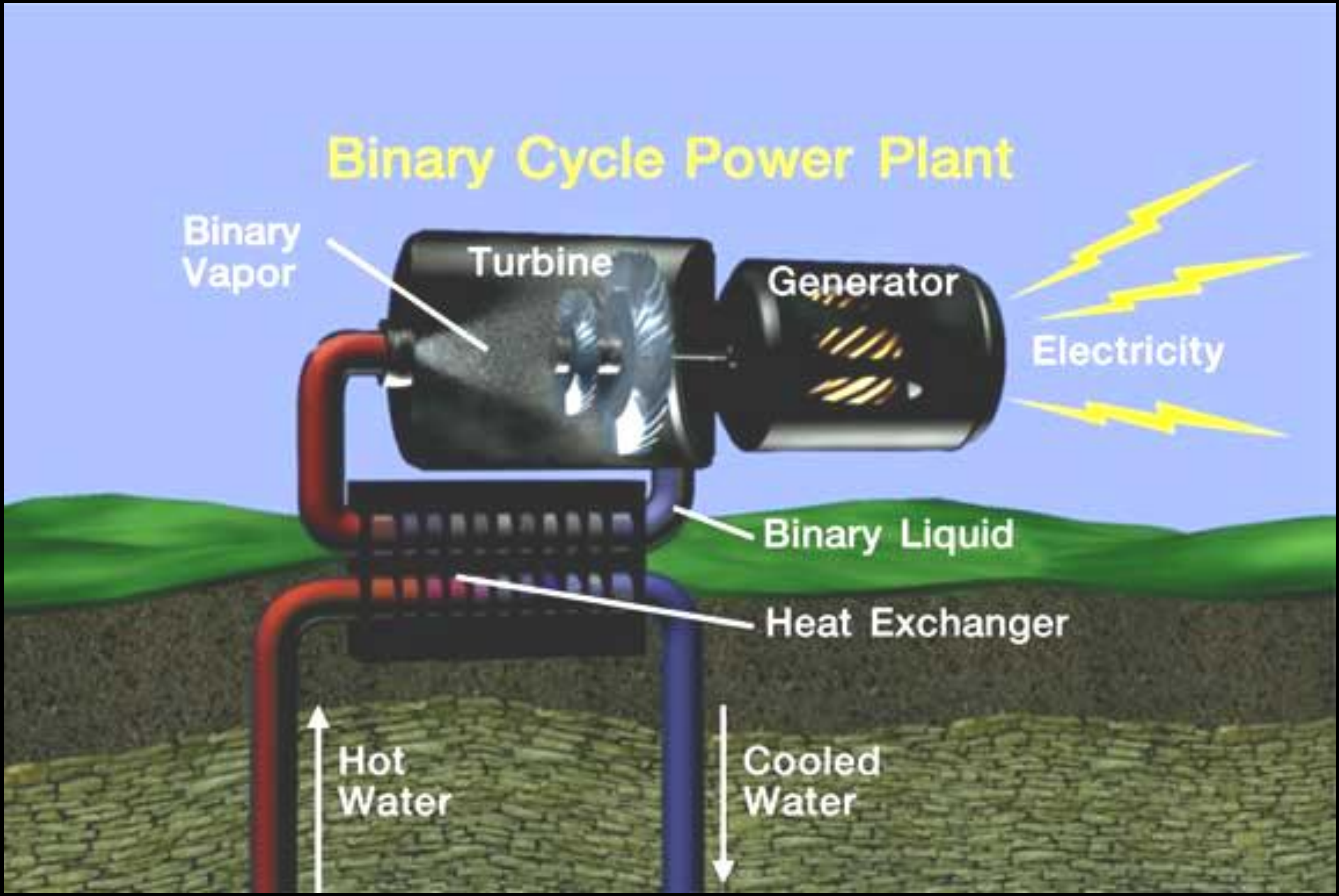
Double-flash power plant with single turbine



Double-flash power plant with separate high- and low-pressure turbines

Flash technology was invented in New Zealand. Flash steam plants are the most common, since most reservoirs are hot water reservoirs. This flash steam plant is in Japan.

In flash plants, both the unused geothermal water and condensed steam are injected back into the periphery of the reservoir to sustain the life of the reservoir.



In a binary cycle power plant (binary means two), the heat from geothermal water is used to vaporize a **"working fluid"** in a separate heat exchanger. **The vapor of the working fluid powers the turbine generator.**

If the geofluid temperature is less than 150ºC, it becomes difficult to build an efficient and economic flash-steam plant.

Binary cycle geothermal plants are then used. A working fluid (different from water), chosen for its appropriate thermodynamic properties, receives heat from the geofluid (in a heat exchanger – the evaporator) where is evaporates, then expandes through a turbine, condenses (in a condenser with cooling water), and is returned to the evaporator by means of a feed pump.

The first geothermal binary power plant was put in operation in Russia (Kamchatka peninsula) in 1976.

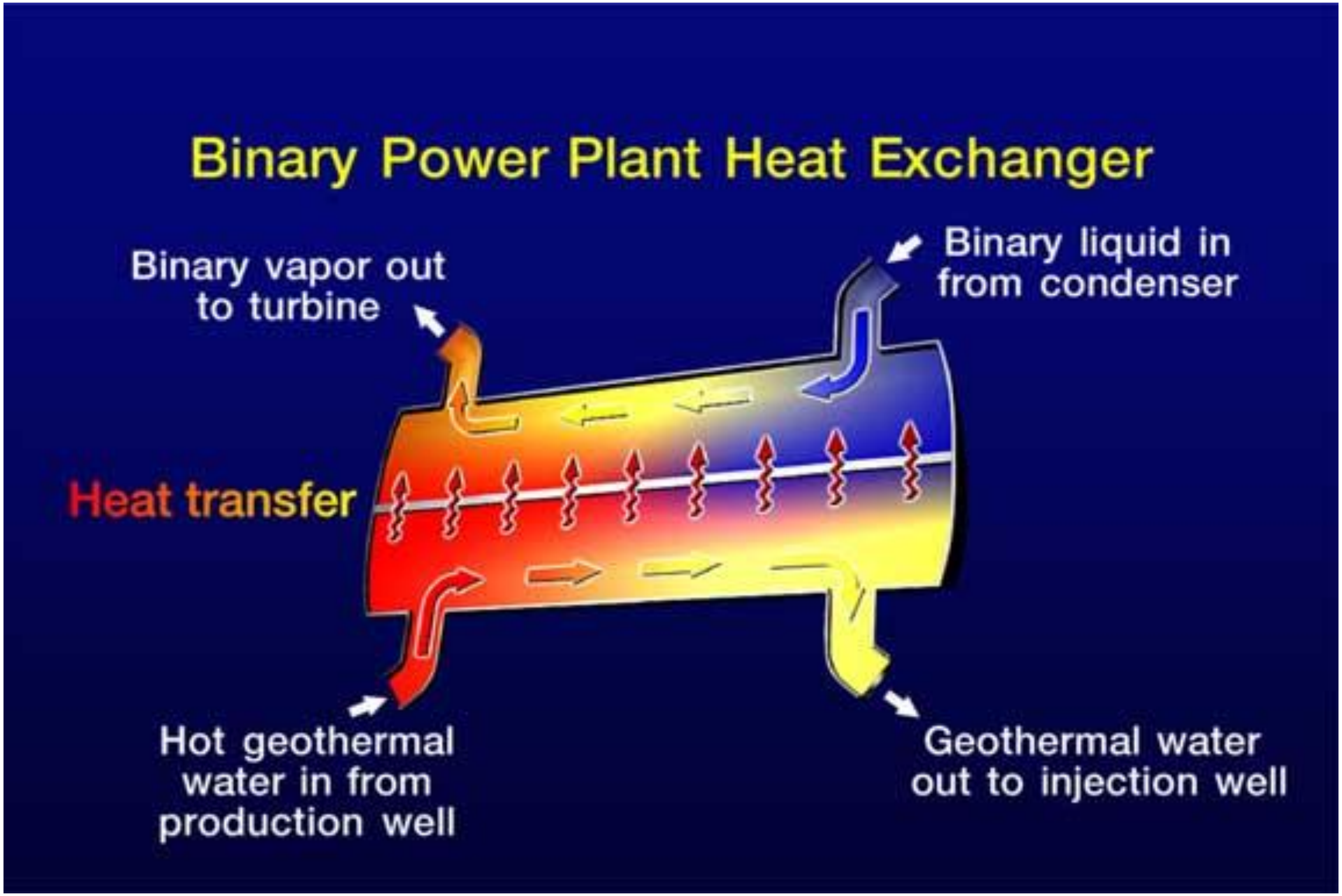
Today binary cycle plants are the most widely used type of geothermal power plants, with 155 units (in 2004) generating 274 MWe. They constitue 33% of all geo-thermal units in operation, but only generate 3% of the total power. The average rating per unit is only 1.8 MW, but units with ratings of 7-10 MW are coming into use with advanced cycle design.

Thermodynamic properties of some candidate working fluids for binary plants (water is shown for comparison)

Fluid	Formula	T_c (°C)	p_c (MPa)	p_s at 300K (MPa)	p_s at 400K (MPa)
Propane	C_3H_8	96.95	206.5	0.9935	n.a.
i-Butane	i-C_4H_{10}	135.9	276.7	0.3727	3.204
n-Butane	C_4H_{10}	150.8	303.4	0.2559	2.488
i-Pentane	i-C_5H_{12}	187.8	370.1	0.09759	1.238
n-Pentane	C_5H_{12}	193.9	380.9	0.07376	1.036
Ammonia	NH_3	133.65	272.6	1.061	10.3
Water	H_2O	374.14	705.5	0.00354	0.2456

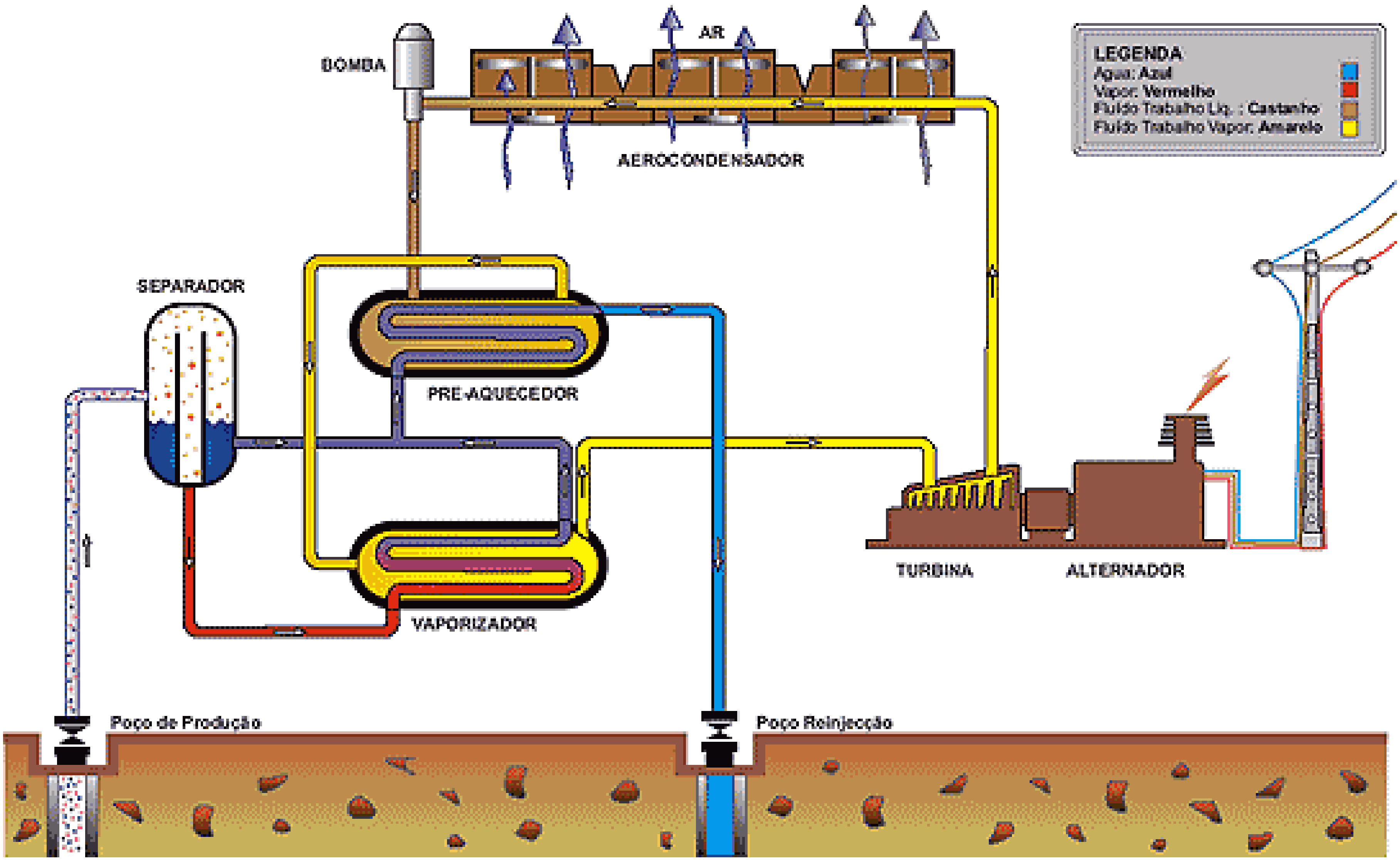
T_c, p_c = temperature, pressure at critical point
p_s = saturated vapour pressure

Note that the temperature and pressure at critical point are substantially lower than for water, while the saturated vapour pressure is substantially higher.



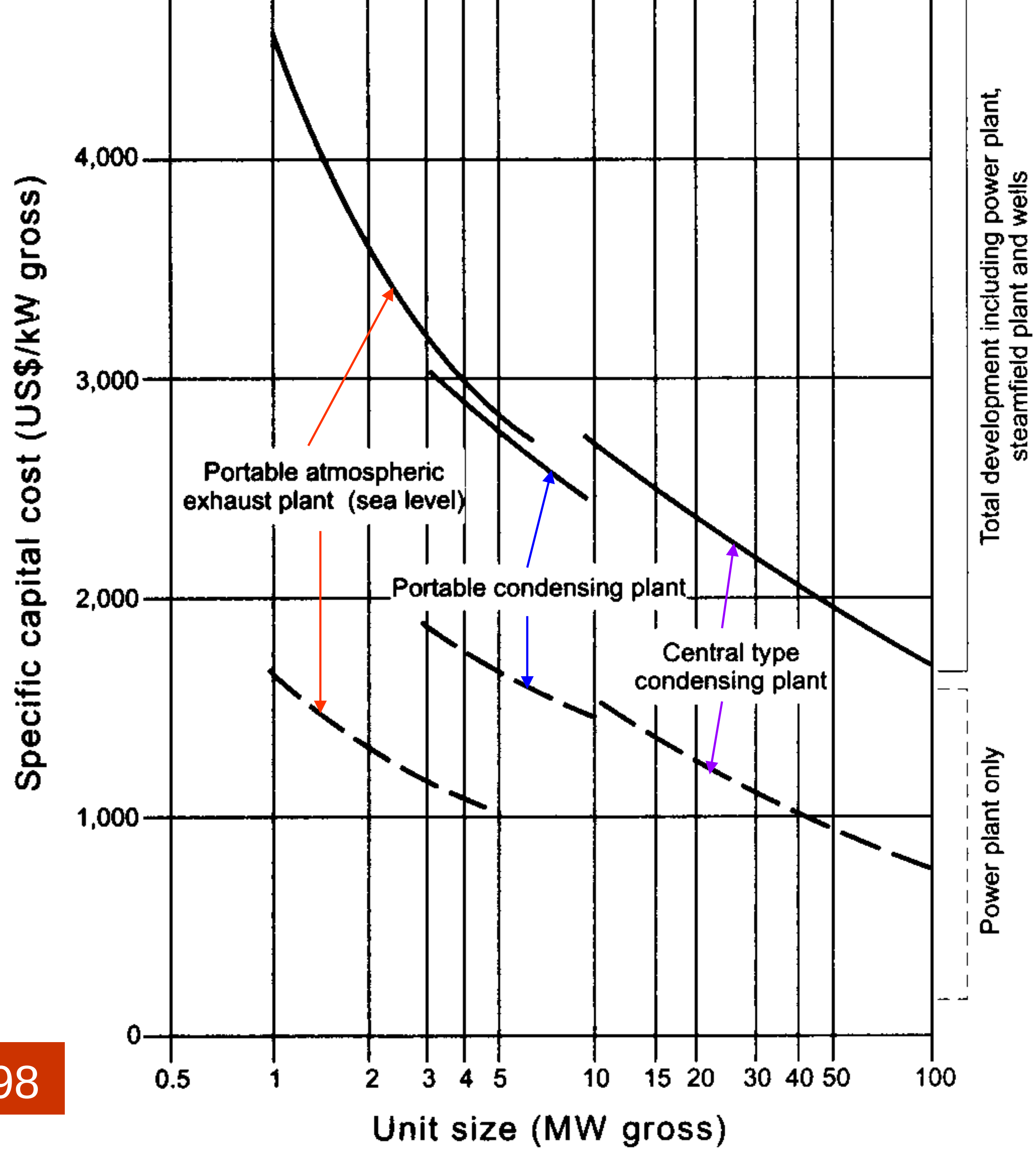
In the heat exchanger, heat is transferred from the geothermal water to a second liquid. The geothermal water is never exposed to the air and is injected back into the periphery of the reservoir.

Binary technology allows the use of lower temperature reservoirs, thus increasing the number of reservoirs that can be used. This binary plant is at São Miguel Island, Azores, Portugal.



Schematic representation of the binary plant at São Miguel Island, Azores.

This power plant provides about 25% of the electricity used on the Big Island of Hawaii. It is a hybrid binary and flash plant.


Specific capital cost (US$/kW gross)
4,000
3,000
2,000
1,000
0
0.5
1
2
3
4
5
10
15
20
30
40
50
100
Unit size (MW gross)
Portable atmospheric exhaust plant (sea level)
Portable condensing plant
Central type condensing plant
Total development including power plant, steamfield plant and wells
Power plant only

Data: 1998

Energy and investment costs for electric energy production from renewables

	Current energy cost US cents/kWh	Potential future energy cost US cents/kWh	Turnkey investment cost US$/kW
Biomass	5–15	4–10	900–3 000
Geothermal	2–10	1–8	800–3 000
Wind	5–13	3–10	1 100–1 700
Solar:			
photovoltaic	25–125	5–25	5 000–10 000
thermal electricity	12–18	4–10	3 000–4 000
Tidal	8–15	8–15	1 700–2 500

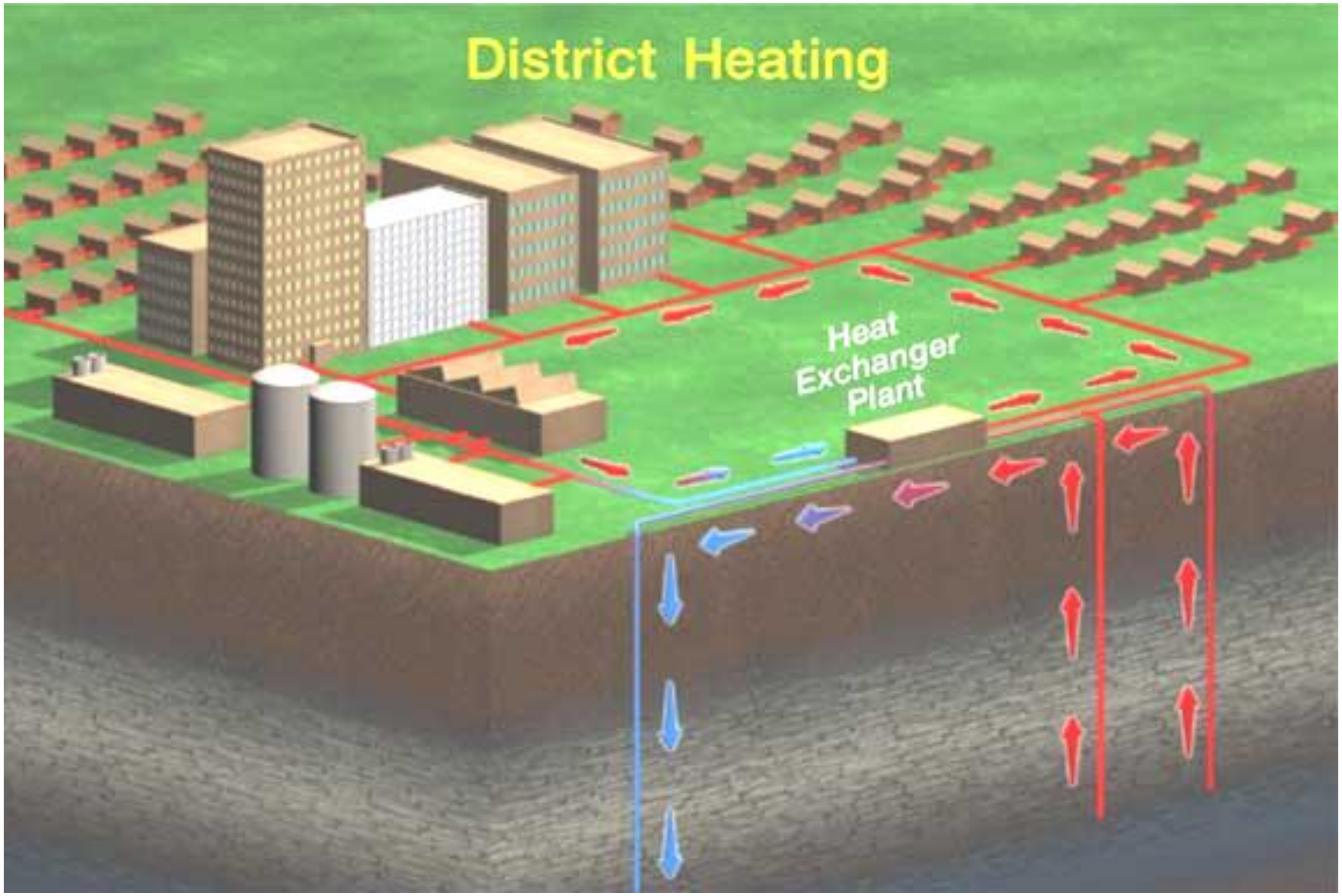
Source: Fridleifsson, 2001.

Installed geothermal electrical generating capacity at the beginning of 2003

Country	Capacity (MWe)	Country	Capacity (MWe)
Austria	1.25	Kenya	53
China	28.2	Mexico	865
Costa Rica	142.5	New Zealand	438
El Salvador	152	Nicaragua	77.5
Ethiopia	8.5	Philippines	1905
Guatemala	28.6	Portugal (Azores)	14
Iceland	200	Russia	73
Indonesia	787.5	Turkey	20.4
Italy	862	USA	2800
Japan	560.9	**TOTAL**	**9028**

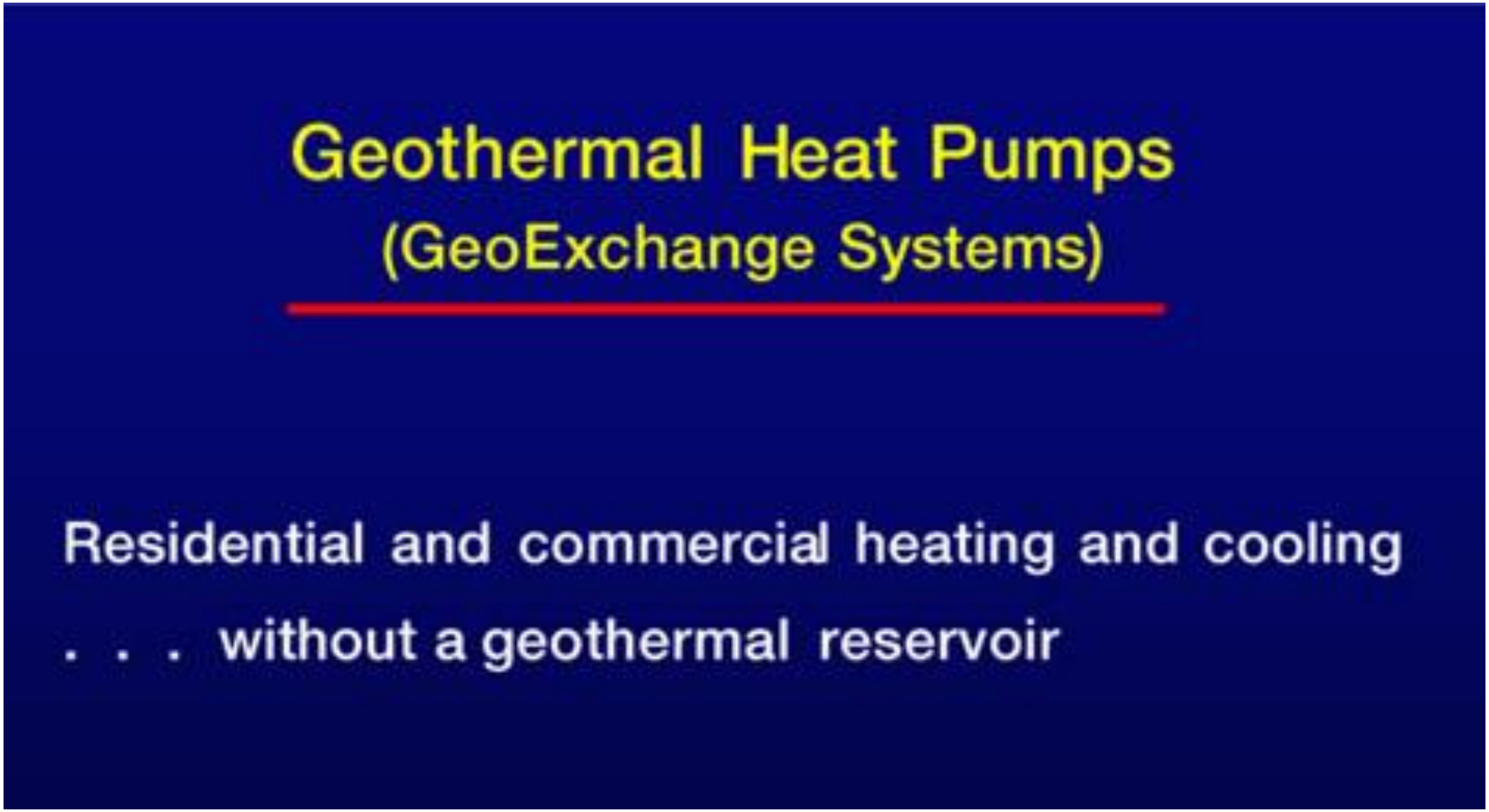

Geothermal Power Plants

District Heating

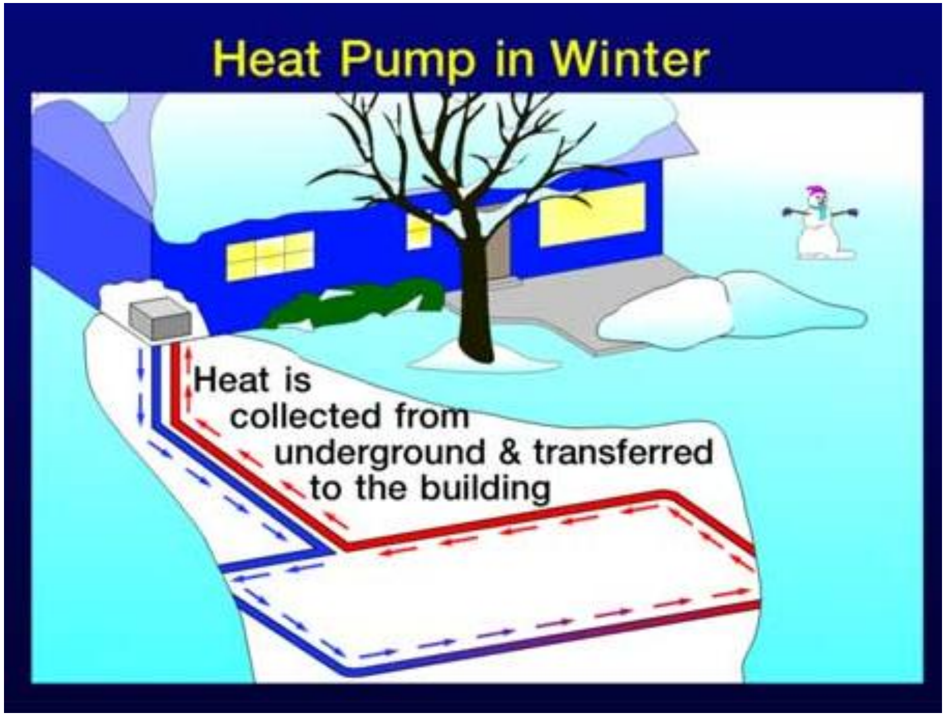


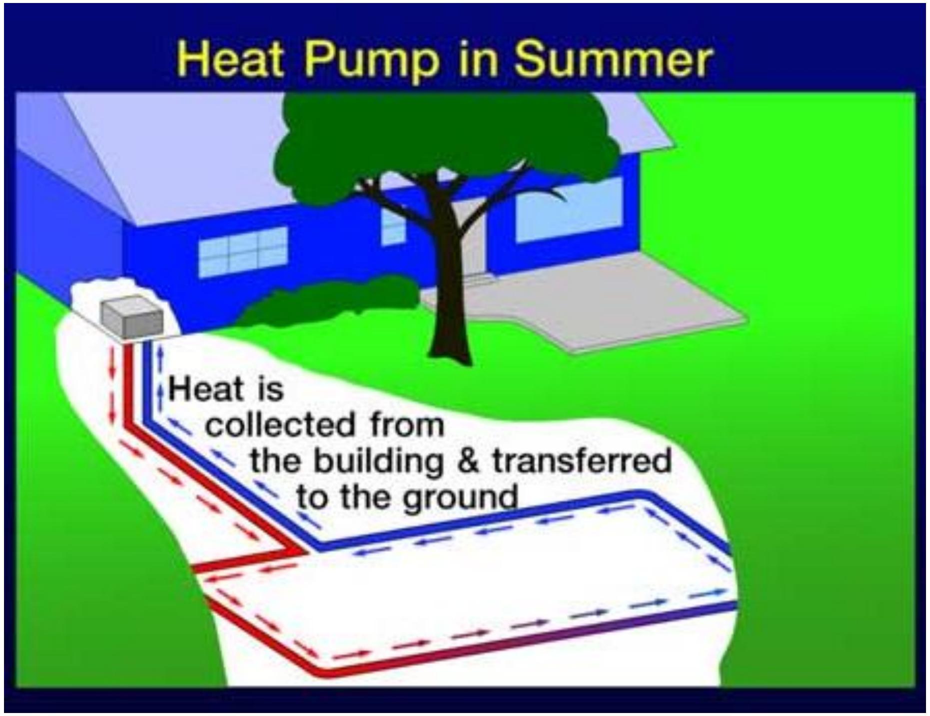
Hot water from one or more geothermal wells is piped through a heat exchanger plant to heat city water in separate pipes. Hot city water is piped to heat exchangers in buildings to warm the air.

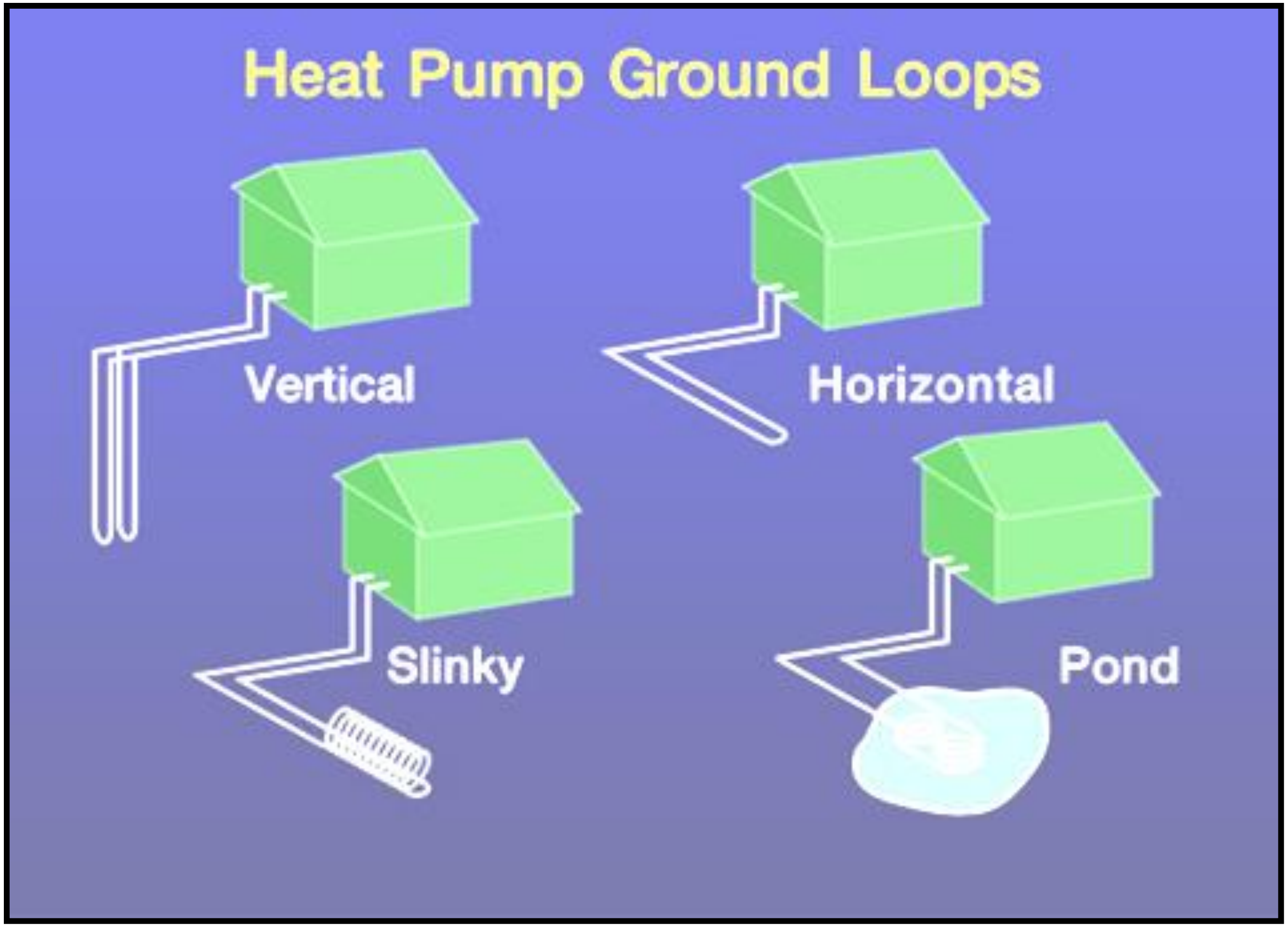
About 95% of the buildings in Reykjavik, Iceland, are heated with geothermal water.



Geothermal heat pumps can be used almost everywhere in the world, without a geothermal reservoir. The insulating properties of the earth, just below our feet, can keep us warm or cool.


Heat Pump in Winter
Heat is
collected from
underground & transferred
to the building


Heat Pump in Summer
Heat is
collected from
the building & transferred
to the ground



Different styles of pipes are installed beside a building. A liquid is piped through the pipes to pick up the heat FROM the ground or (in the summer) to bring heat from the building TO the ground.

Benefits of Geothermal Heat Pumps:

- Can be used almost everywhere worldwide.
- Are energy- and cost-efficient.
- Conserve fossil fuel resources.
- Provide clean heating and cooling – no emmissions from burning fuels.

The U.S. Environment Agency has rated geothermal heat pumps among the most efficient heating and cooling technologies available today.

400 thousand heat pumps in USA, providing 1500 thermal MW of heating and cooling.

Many of these slides have been adapted from a slide show prepared by **The Geothermal Education Office, USA.**

Available at: http://geothermal.marin.org/GEOpresentation/

Bibliography:

• Mary H. Dickson, Mario Fanelli. Geothermal Energy: Utilization and Technology. UNESCO Publishing, 2003. ISBN 9231039156. Covers all aspects of geothermal energy.

• Ronald DiPippo. Geothermal Power Plants. Elsevier, 2005. ISBN 1856174743. Advanced text on electrical energy production.

• Frank Press, Raymond Siever. Understanding Earth. W.H. Freeman, 1994. ISBN 0716722399. A very well illustrated introduction to the geology of the Earth, by two well-known scientists.

• Geoff Brown, John Garnish. Geothermal Energy. In: Renewable Energy (Godfrey Boyle, editor). Oxford University Press, 2004. ISBN 0199261784. A basic introduction to the subject.